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Spatial frame class

1. Database identifier.
2. The parent spatial frame.
3. The list of children spatial frames.
4. A static hash table that provides the address of a spatial frame given a database identifier.
5. The outermost grid cell boundary, given as a pair of synchronized lists.
   a. The first list is a set of IJK base grid cells. The second list is in 1-1 correspondence with the first list.
   b. The second list is an ordered list of {left/right, up/down…} steps that define the grid cell face sequence that form the boundary.
6. The boundary curve contents of the grid cell boundary.
   a. Mandatory is a list of minima, maxima, and inflection points, ordered by arc length coordinate from the first critical point in this list.
   b. Optional is a list of conic sections that approximate the shape of the boundary restricted to each consecutive pair of critical points.
7. Transition zone, given as a grid cell thickness surrounding the interior of the outermost boundary. Zero thickness is acceptable.
8. The list of data base identifiers used to define the surfaces that intersect this spatial frame.
9. The data base identifier of the octree attached to this spatial frame.
10. Shape contents enclosed by the outer boundary. This can be void when the frame defines a hole.
11. Methods
    a. Put/GetNeighbor

b. Put/GetLogicalNeighbor
c. Put/GetShapeContents
d. Put/GetSurfaceContents
e. ReseampleSurface
f. Put/GetOuterBoundary
g. Put/GetInnerSpatialFrameList
h. Put/GetParentSpatialFrame
i. Put/GetTemporalFrame

12. Evolutionary law
    a. Parameter list
    b. Boundary conditions
    c. Initial conditions
    d. Status

Shape index manifold

1. Database identifier
2. Status
3. Floating point references
    a. XYZ
    b. ABC
4. Misfit threshold
5. Shape index charts
6. Boundary representation node

Shape index chart

1. Database identifier
2. Symmetry group isomorphism class
   {Sphere, Cylinder, Cone, Frustum, Torus, Ellipsoid, Hyperboloid_Type_I, Hyperboloid_Type_II, Circle, Ellipse, Cube, Tetrahedron, Square, Triangle, Rectangle, Cyclide, Trivial}
3. Parameter vector ABC
4. Canonical position transformation [Rotation matrix and translation vector]

5. Shape index manifold
6. Shape index interval
7. Critical point list
8. (Static) analytical methods
    a. Evaluator
    b. Normal
    c. Tangent
    d. First Fundamental Form
    e. Christoffel symbols
    f. Second Fundamental Form
    g. Gaussian curvature
    h. Mean curvature
    i. Principal curvature
    j. Shape index
    k. Signed distance function
    l. Closest point transform
    m. Parameter estimation
    n. Extrude
    o. Offset
    p. Adaptive sampling
9. Standard methods
    a. Sve
    b. Restore
    c. I/O compress
    d. I/O decompress
    e. Delete
    f. Copy
    g. Newa
10. Misfit reduction
    a. Absolute amount
    b. Relative amount
    c. Base type
       {Ellipse, Circle, Square, Triangle, Rectangle}
    d. Parameter vector list
       {u, v, normal offset}

1D Boundary

1. Conic section class
   - {Ellipse, Circle, Line, Parabola, Hyperbola
2. Plus side
   a. Shape index chart
   b. UV start stop
3. Minus side
   a. Shape index chart
   b. UV start stop
4. Boundary representation node

Critical point assertion

(We specify two lists, separating min/max from saddle point.)

1. Shape index chart
2. UV location
3. Chart symmetry

We use Dustin Lister's trick of using a 2s complement 16-bit integer to subdivide length scale field data into (+/-) 32K increments. Given a reservoir model of size 9 square miles by 50000 feet, we can resolve data to 1 cm. Applying Dustin's idea to Shape index charts and dependent lists, we obtain a surprisingly compact data structure. For example, suppose that a shape index manifold contains 48 charts such that each chart supports 48 misfit reduction "boxes". Further, suppose that each chart contains 4 critical point orbits relative to the chart symmetry group. Then the Shape Index manifold will consume on the order of 34000 bytes ≈ 33 Kbytes of memory. These choices are arbitrary, but far exceed the empirically estimated values for the Top of Salt surface in the November 2002 Implicit Surface Proof of Concept

data set. In that demonstration, this surface consumed slightly more than 1 MByte of memory, which implies that curvature-based methods are naturally 30 times more conservative in memory utilization.

Quadratic Taylor expansion disk class

1. Status {CRITICAL_POINT_EXPANSION}
2. Expansion point
3. Principal curvatures
4. Rotation matrix and translation vector
5. Error tolerance
6. Shape index interval
7. Trimming curve discrete samples list

Characteristic length scale cone class

1. Equivalence class
2. Status
3. Length scale
4. Top
    a. Radius
    b. Center
    c. Percent error
5. Bottom
    a. Radius
    b. Center
    c. Percent error
6. Slant height ratio

An example of applying the techniques described above to a relatively complicated surface will now be discussed. The example used herein is a synthetic surface designed to be an "unfriendly" test case.

Approximately 14500 triangles were created from 7349 vertices. The representation requires approximately 1Mb of memory.

Note that discrete estimators for Gaussian and mean curvature were used to compute the shape index. See, M. Desbrun, M. Meyer, P. Schroeder, A. Barr, Discrete Differential-Geometry Operators in nD, Technical Report Caltech, 2000. For example, the discrete estimator for mean curvature H*(P) evaluated at a point P is

$$H^*(P) = \frac{1}{4 * area} \sum_i (\cot \alpha_i - \cot \beta_i) \cdot (P - Q_i)$$

Figure 42 is a schematic illustration of the definition of the variables in the mean curvature estimator. See, G. Stylianou, Comparison of triangulated surface smoothing algorithms, http://3dk.asu.edu/archives/seminars/ presentation/Compsmthal.ppt.

The discrete Gaussian curvature estimator K*(P) evaluated at a point P is given by

$$K^*(P) = 2\pi - \sum_i \theta_i(P),$$

where θ_i *is the* i^{th} *triangle's angle in the star of P rooted to P.*

Figure 43 is an image of the co-triangulated irregularly spaced mesh that represents the present example of the top of the salt.

Several smoothing methods for triangulated surfaces have been considered, but all of them assume a regular spaced carrier grid. See, A. Hubeli, Multiresolution Techniques for Non-Manifolds, Diss ETH No. 14625, Computer Graphics Laboratory, Department of Computer

Science, ETH Zurich, 2002. This surface is sampled irregularly, the mesh surface is re-samples by interpolating missing sample points. Figure 44 shows the surface when re-sampled by interpolating missing sample points. The surface of Figure 44 has approximately 10000 points versus 7900 points in the original mesh shown in Figure 43.

The surface of Figure 44 is noisy everywhere, but the noise is low amplitude. The preferred smoothing software according to A. Hubeli, Multiresolution Techniques for Non-Manifolds, Diss ETH No. 14625, Computer Graphics Laboratory, Department of Computer Science, ETH Zurich, 2002, incorporated herein by reference. The smoothing software moves points in the horizontal plane to minimize curvature, so it is necessary to project one version of the surface onto another when different numbers of iterations are applied

Figure 45 shows the re-sampled surface after 25 iterations of smoothing. This surface is significantly smoother, but after comparing the two images we concluded that we have not sacrificed its intrinsic low frequency contents. The mean curvature flow preferentially removes high frequency noise and leaves intact low frequency intrinsic shape.

Figure 46 shows the shape index map for the re-sampled triangulated surface after 25 iterations. There are regions of approximately the same shape index that contain islands that have significantly different shape index. An example of this behavior is the red body in the bottom middle that contains two blue bodies.

We consider the following labeling options for this image. We recall that "label" is a grid cell equivalence class identifier.

1. Label each blue body and the surrounding red body as separate shapes.
2. Label the two blue bodies as part of the same shape and consider the blue shape to be distinct from the enclosing red shape.
3. Label the red body as blue body misfits.
4. Label the blue bodies as red body misfits.

Figure 47 shows that there are 33 shapes in the example. According to the data structure definition described above, about 512 bytes of storage are needed to express a shape with zero misfit reduction. Assuming adequate misfit reduction per shape consumes another 512 bytes, we conclude that we can well approximate this noisy surface in 33 Kbytes of data structure. We need about 1 Mbytes of storage to define this surface, so we obtain a 1000 / 33 ≈ 30-fold compression.

It is important to understand that we do not equate a geometrical label to a geological theory. We prefer a description of the topography that uses the least number of parameters.

According to preferred embodiments of the invention an important implicit surface data structure is the narrow band octree. The curvature analytical enhancements to implicit surface technology described herein enable the construction a reservoir framework using significantly less memory and CPU than conventional triangulated surface technology requires. Additionally,

the curvature-based methods describe herein enable the construction of a new generation of structural framework. We enumerate a number of advantages of curvature analysis in support of implicit surface methods, according to preferred embodiments of the present invention.

I. Computer resource economy

a. We describe the shape of a geological surface in terms of explicit surface forms, e.g., ellipsoid and torus, rather than contextually in terms of a technology used to represent shape, e.g., triangles.

b. We replace numerical computation of curvature, normals, signed distance functions, etc. by analytical formulae which enables us to drop the buffering needed to hold the sampled data.

II. Surface flattening

c. Many operations on surfaces are easier to perform when a flattened version of a surface is available.

d. We refer to the flattening as the "parameterization" of the surface.

e. When we construct the parameterization of a surface, then we also generate an estimate of the geometric strain needed to flatten the surface. Strain says how comparable is the flattened version to the given surface.

f. Parameterization is much more useful if the flattened surface can be placed in the framework, rather than on some planar surface that is outside the framework. Shape analysis enables us to embed the parameter space surface in our xyz coordinate space.

III. 3D conformal grid generation and forensic reconstruction

g. Using surface parameterisation, shape analysis knows how extract a 3D conformal grid from each framework sub-volume.

h. Regular grids are convenient for simulation. That does not mean that we have to permanently record a regular sampling in regions that show little or no variation. We equate this variation to an estimate of curvature. On demand we provide regularly spaced samples in low curvature regions.

i. We call this curvature-adaptive sampling. Curvature adaptive sampling does not waste space on recording redundant information.

j. Curvature-dependent adaptive grid generation is more economical than the non-curvature-adaptive form. An application can easily extract a perfectly uniform 3D grid on demand.

k. Mean curvature flow can be used to fill in holes and to construct a plausible representation of an eroded region of a sequence.

IV. Framework construction, editing, and reconstruction

l. Based on the implicit surface's signed distance function, we construct a connected sum of shapes that are sectors of a conic section fibre bundle.

m. Boolean operations that take shape into account are more efficient than those that do not.

n. Sending and receiving elementary shape descriptions is inherently more efficient than sending and receiving the corresponding triangulation. The Marching Cubes algorithm can be used to triangulate an implicit surface's elementary shape constituents.

o. The identification of elementary shapes is based on application of mean curvature flow (mcf).

p. We do not worry if a process is well approximated by mcf. Rather all that matters is whether the elements in a framework can be defined as the solution to a flow problem.

q. We use structure synopsis diagrams to send and receive a high level resume of the connectivity and shape of a structural framework. This data structure extends the traditional Reeb graph summary of connectivity to a shape description that is intuitive - which is something a byte stream describing millions of triangles can never hope to achieve.

V. Noise suppression

r. Elementary shape identification can be applied to a noisy surface.

s. Shape analysis provides a tool to distinguish noise suppression from shape decay.

VI. Robust shape identification

t. Suppose that an implicit surface is represented in a 3D grid with a tri-linear interpolation function. We have discovered necessary conditions on the interpolation function coefficients in order that a grid cell in the grid contain a critical point. It is very easy and fast to test these conditions, so we can quickly locate a surface's critical points in the grid.

u. Group theory yields a robust classification of symmetry induced from the tri-linear interpolation approximation of the implicit surface's signed distance function. This is used to identify the optimal elementary shape

candidate shape that fits a single grid cell of the 3D grid representation of the implicit surface.

v. It enables local quantitative comparison of two surface shapes. The process identifies regions on the measured surface where there is poor agreement and provides an estimate of the energy expended in the geometrical transformation needed to finish the package.

Figure 48 is a schematic illustration of a system for improved extraction of hydrocarbons from the earth, according a preferred embodiment of the invention. Seismic sources 150, 152, and 154 are depicted which impart vibrations into the earth at its surface 166. The vibrations imparted onto the surface 166 travel through the earth; this is schematically depicted in Figure 7 as arrows 170. The vibrations reflect off of certain subterranean surfaces, here depicted as surface 162 and surface 164, and eventually reach and are detected by receivers 156, 158, and 151.

Each of the receivers 156, 158, and 151 convert the vibrations into electrical signals and transmit these signals to a central recording unit 170, usually located at the local field site. The central recording unit 170 typically has data processing capability such that it can perform a cross-correlation with the source signal thereby producing a signal having the recorded vibrations compressed into relatively narrow wavelets or pulses. In addition, central recording units may provide other processing which may be desirable for a particular application. Once the central processing unit 170 performs the correlation and other desired processing, it

communicates the seismic data to data processor 180 which is typically located at the local field site. The data transfer from the central recording unit 170 in Figure 7 is depicted as arrow 176 to a data processor 180. Data processor 180 can be used to perform processing as described in steps 300 to 316 in Figure 50 and 330 to 340 in Figure 51, as is described more fully below.

The seismic data collected from recording unit 170 which is usually a relatively large data set. Importantly, according to the invention, the data processing to generate an efficient and robust subdivision of shapes representing the seismic data is performed on data processor 180. In this way a compressed, stable, accurate representation of new data is transmitted to other processing centers.

At the field site, a subset 182 of a larger earth model 192 is provided to aid in the field activities. The after the subdivision of shapes, the Fragment earth model 182 can be updated with the newly acquired data for use locally.

Data processing center 190 is located away from the wellsite or field site, typically at an asset management location. In some cases data processing center 190 is physically distributed across a number of separate processing centers over a wide geographic region. Data processing center 190 integrates the subdivision of shapes representing the earth structures into existing earth model 192. The integration of both the geometry framework and material field properties is preformed. While in some cases the integration of the new shape information can be done at the field site, this is not normally done due to a number of factors including (1)

lack of full data set of earth model at the field site, lack of computational facilities, and lack of sufficient local expertise.

Once the earth model 192 is updated with the newly acquired information, updated earth model data from model 192 is preferably sent back to the field site data processor 180. The information sent back to the field site preferably includes both (1) shape information to update geometry framework and material field properties of earth model fragment 182, and (2) decisions relevant to field site activities based in part on the updated earth model 192.

For example, according to one embodiment, based on new information integrated in earth model 192 at data processing center 190, improved predictions of fluid flow are made though the earth structures. Based on these improved predictions the rate of extraction from production well 114 is preferably altered using surface equipment 116 to optimize production rates from reservoir rock 120 while minimizing likelihood of undesirable events such as water breakthrough.

According to an embodiment during the wellbore construction, based on new information integrated in earth model 192 at data processing center 190, improved predictions on the likelihood of structural failure of a wellbore 110 being drilled into reservoir rock 120 from drilling rig 112. Based on these improved predictions, the drilling plan used to drill the well 110 is preferably updated, for example to reduce the risk of wellbore stability problems, to steer the drilling activity more precisely to certain locations within the reservoir rock and/or avoid faults, etc.

According to another embodiment of the invention, data processing center 190 can more easily communicate geologic information from one earth model based on geometrical representation to another earth model based on a different geometrical representation. In this way, the invention can be used to facilitate communication of earth model information between different models. Similarly, according to another embodiment of the invention, the techniques described her used to facilitate the aggregation of geologic information from a number of geometrical representations of the earth structures.

Figure 49 shows further detail of data processor 180, according to preferred embodiments of the invention. Data processor 180 preferably consists of one or more central processing units 350, main memory 352, communications or I/O modules 354, graphics devices 356, a floating point accelerator 358, and mass storage such as tapes and discs 351.

Figure 50 shows steps in a method for processing data used for hydrocarbon extraction from the earth, according to preferred embodiments of the invention. In step 300, sampled data representing earth structures is received. In step 310 one more symmetry transformation groups are identified from the sampled data. In step 312, a set of Morse theoretical height field critical points are identified from the sampled data. In step 314, a plurality of subdivisions of shapes are generated such that when aggregated, the subdivisions accurately, efficiently, and robustly represent the original earth structures. The generation in step 314 is based on the set of identified critical points and the symmetry transformation groups, according to the techniques

descried above and in further detail in Figure 51. In Step 316, earth model data is processed using the generated subdivision of shapes. In step 318 activity relating to extraction of hydrocarbons from a hydrocarbon reservoir is altered based on the processed earth model data. Various embodiments involving processing of earth model data and altering activity in steps 316 and 318 are described above with respect to Figure 48.

Figure 51 shows further detail of steps in generating an efficient and robust subdivision of shapes, according to preferred embodiments of the invention. In step 330, each of the identified symmetry transformation groups is preferably associated with to a plurality of shape families. Each of the shape families preferably includes a set of predicted critical points. The shape families for each symmetry transformation group are preferably contained in a lookup table. In step 332 a shape family is selected from the plurality of shape families. The selection is preferably based on closeness of correspondence, or best fit, between the identified critical points from the original sampled data and the predicted critical points of the selected shape family.

Note that each of the symmetry transformation groups is preferably a set of diffeomorphisms that act on a topologically closed and bounded region in space-time such that under transformation the region occupies the same points in space.

Each shape family preferably has an associated set of symmetry transformation group orbits, each orbit being associated with orbit information that specifies whether the orbit contains a predicted critical point and value of the Gaussian curvature of a point in the orbit. In

step 334, the orbit information from the set of symmetry transformation group orbits associated with the selected shape family is preferably applied to the original sampled data. In step 336 the result of step 334 yields a unique specification of a shape from the selected shape family. In step 338, each of the plurality of subdivisions of shapes is preferably generated by identifying a part of the uniquely specified shape that corresponds to the sampled data. In step 340, the identified parts are assembled, or sewn together, such that a representation of the earth structures is generated.

The assembled subdivisions are advantageously more efficient and robust than conventional methods. For example the number of parameters in each subdivision times the number of subdivisions is substantially less then would be needed using a faceted representation method, and the plurality of subdivisions is more numerically stable than third order or higher representation.

While the invention has been described in conjunction with the exemplary embodiments described above, many equivalent modifications and variations will be apparent to those skilled in the art when given this disclosure. Accordingly, the exemplary embodiments of the invention set forth above are considered to be illustrative and not limiting. Various changes to the described embodiments may be made without departing from the spirit and scope of the invention.

CLAIMS

What is claimed is:

1. A method for processing data used for hydrocarbon extraction from the earth comprising the steps of:

receiving sampled data representing earth structures;

identifying one more symmetry transformation groups from the sampled data;

identifying a set of critical points from the sampled data;

generating a plurality of subdivisions of shapes the subdivisions together representing the earth structures, the generation being based at least in part on the set of identified critical points and the symmetry transformation groups;

processing earth model data using the generated subdivision of shapes; and

altering activity relating to extraction of hydrocarbons from a hydrocarbon reservoir based on the processed earth model data.

2. A method according to claim 1 wherein the identified symmetry transformation group is a set of diffeomorphisms that act on a topologically closed and bounded region in space-time such that under transformation said region occupies the same points in space.

3. A method according to claim 1 wherein each of the identified symmetry transformation groups corresponds to a plurality of shape families.

4. A method according to claim 3 wherein each of the plurality of shape families comprises a set of predicted critical points.

5. A method according to claim 4 wherein the step of generating subdivisions comprises selecting a shape family from the plurality of shape families that corresponds to the identified symmetry transformation group, said selecting being based on closeness of correspondence between the identified critical points from the sampled data and the predicted critical points of the selected shape family.

6. A method according to claim 5 wherein each shape family has an associated set of symmetry transformation group orbits, some of the orbits being associated with critical points and other orbits being associated with distinguished Gaussian curvature values.

7. A method according to claim 6 wherein each symmetry transformation group orbit of the selected shape family is associated with orbit information that specifies whether the orbit contains a predicted critical point and value of the Gaussian curvature of a point in the orbit.

8. A method according to claim 7 wherein the orbit information from the set of symmetry transformation group

orbits associated with the selected shape family is applied to the sampled data thereby generating a unique specification of a shape from the selected shape family.

9. A method according to claim 8 wherein each of the plurality of subdivisions of shapes is generated by identifying a part of the uniquely specified shape that corresponds to the sampled data.

10. A method according to claim 9 wherein the identified parts of the uniquely specified shapes are assembled, thereby generating a representation of the earth structures.

11. A method according to claim 10 wherein the generated representation is continuous.

12. A method according to claim 11 wherein the generated representation is smooth.

13. A method according to claim 9 wherein the uniquely specified shapes are specified using differentiable functions including one or more of the following types: surfaces derived from conic sections, splines, general polynomials and trigonometric functions.

14. A method according to claim 1 wherein the sampled data is smoothed prior to said steps of identifying critical points and identifying one or more symmetry transformation groups.

15. A method according to claim 1 wherein the identified critical points are Morse theoretical height field critical points consisting of the following three types: minima, maxima and saddle points.

16. A method according to claim 15 wherein said step of generating a plurality of subdivisions comprises applying a canonical homogeneous transform such that the number of parameters needed to uniquely describe a shape in the earth structure is minimized.

17. A method according to claim 1 wherein the earth model data is geologic data, geophysical data, petrophysical data, mechanical earth model data and/or reservoir fluid flow data.

18. A method according to claim 1 wherein earth model data is processed such that earth models are updated, alternative versions of existing earth models are created, time-lapse earth models are generated and/or the earth model data is distributed to other earth models or other applications.

19. A method according to claim 1 wherein the sampled data represents sampled physical structure and material properties of the earth structures.

20. A method according to claim 1 wherein said step of processing earth model data comprises making predictions of fluid flow though at least some of the earth structures and wherein the altered activity is

altering the rate of extraction based on said predictions.

21. A method according to claim 1 wherein said step of processing earth model data comprises predicting the likelihood of structural failure of a wellbore though at least some of the earth structures and wherein the altered activity is altering the drilling of the wellbore based on the predicted likelihood of failure.

22. A method according to claim 1 wherein said step of processing earth model data comprises communicating geologic information relating to at least some of the earth structures between a first geometrical representation and a second geometrical representation of the earth structures.

23. A method according to claim 1 wherein said step of processing earth model data comprises aggregating information from a plurality of geometrical representations of the earth structures and wherein the altered activity is based at least in part on the aggregated information.

24. A method according to claim 1 wherein said step of processing earth model data comprises constructing an earth model to a user specified error tolerance using the generated subdivision of shapes.

25. A method according to claim 1 wherein each of the plurality of subdivisions of shapes is generated by identifying a part of a uniquely specified shape that corresponds to the sampled data.

26. A method according to claim 1 wherein the step of generating a plurality of subdivisions comprises the steps of:

analyzing curvature of the sampled data thereby generating a shape index field; and

identifying functions that fit the shape index field.

27. A method according to claim 26 wherein the functions are differentiable.

28. A method according to claim 1 wherein the plurality of subdivisions are generated such that the number of parameters in each subdivision times the number of subdivisions is substantially less then would be needed using a faceted representation method.

29. A method according to claim 1 wherein the plurality of subdivisions are generated such that they are more numerically stable than third order or higher representation.

30. A method according to claim 1 wherein the sampled data is a faceted representation of the earth structures.

31. A method according to claim 30 wherein the faceted representation is a triangle mesh.

32. A method according to claim 30 wherein the faceted representation is a grid.

33. A method according to claim 1 wherein the sampled data is data measured with seismic acquisition equipment.

34. A method according to claim 33 wherein said steps of receiving, identifying one or more symmetry transformation groups, identifying a set of critical points and generating a plurality of subdivisions of shapes are preformed at or near the location where the sample data is measured.

35. A method according to claim 34 wherein said step of processing earth model data is performed in one or more locations remote from the location where the sample data is measured.

36. A system for improved extraction of hydrocarbons from the earth comprising:

a storage system adapted to receive and store sampled data representing earth structures;

a processing system adapted to identify one more symmetry transformation groups from the sampled data, identify a set of critical points from the sampled data, and generate a plurality of subdivisions of shapes the subdivisions together representing the earth structures, the generation being based at least in part on the set of identified critical points and the symmetry transformation groups;

a earth model processing system adapted to processes earth model data using said generated subdivision of shapes; and

a user interface to display the processed earth model data to personnel such that decisions can be made to alter activity relating to extraction of hydrocarbons from a hydrocarbon reservoir based on the processed earth model data.

37. A system according to claim 36 wherein the identified symmetry transformation group is a set of diffeomorphisms that act on a topologically closed and bounded region in space-time such that under transformation said region occupies the same points in space.

38. A system according to claim 36 wherein each of the identified symmetry transformation groups corresponds to a plurality of shape families, each of which comprises a set of predicted critical points.

39. A system according to claim 38 wherein the subdivisions are generated such that a shape family is selected from the plurality of shape families that corresponds to the identified symmetry transformation group, said selecting being based on closeness of correspondence between the identified critical points from the sampled data and the predicted critical points of the selected shape family.

40. A system according to claim 39 wherein each shape family has an associated set of symmetry transformation group orbits, each orbit being associated with orbit information that specifies whether the orbit contains a predicted critical point and value of the

Gaussian curvature of a point in the orbit, and wherein the orbit information from the set of symmetry transformation group orbits associated with the selected shape family is applied to the sampled data thereby generating a unique specification of a shape from the selected shape family.

41. A system according to claim 40 wherein each of the plurality of subdivisions of shapes is generated by identifying a part of the uniquely specified shape that corresponds to the sampled data, and wherein the identified parts are assembled, thereby generating a representation of the earth structures.

42. A system according to claim 36 wherein the plurality of subdivisions are generated such that the number of parameters in each subdivision times the number of subdivisions is substantially less then would be needed using a faceted representation method.

43. A system according to claim 36 wherein the plurality of subdivisions are generated such that they are more numerically stable than third order or higher representation.

44. A system according to claim 36 wherein the sample data are acquired from the earth structures using seismic acquisition equipment, the storage system and the processing system are located at or near the location where the sample data are acquired, and the earth model processing system is located in one or more locations remote from the location where the sample data is acquired.

45. A computer readable medium capable of causing a computer system to carry out the following steps for processing data relating to earth structures for the extraction of hydrocarbons comprising:

receiving sampled data representing earth structures;

identifying one more symmetry transformation groups from the sampled data;

identifying a set of critical points from the sampled data; and

generating a plurality of subdivisions of shapes the subdivisions together representing the earth structures, the generation being based at least in part on the set of identified critical points and the symmetry transformation groups, wherein earth model data is processed using the generated subdivision of shapes and activity relating to extraction of hydrocarbons from a hydrocarbon reservoir is altered based on the processed earth model data.

46. A computer readable medium according to claim 45 wherein each of the identified symmetry transformation groups corresponds to a plurality of shape families, each of which comprises a set of predicted critical points.

47. A computer readable medium according to claim 46 wherein the subdivisions are generated such that a shape family is selected from the plurality of shape families that corresponds to the identified symmetry transformation group, said selecting being based on closeness of correspondence between the identified

critical points from the sampled data and the predicted critical points of the selected shape family.

48. A computer readable medium according to claim 47 wherein each shape family has an associated set of symmetry transformation group orbits, each orbit being associated with orbit information that specifies whether the orbit contains a predicted critical point and value of the Gaussian curvature of a point in the orbit, and wherein the orbit information from the set of symmetry transformation group orbits associated with the selected shape family is applied to the sampled data thereby generating a unique specification of a shape from the selected shape family.

49. A computer readable medium according to claim 48 wherein each of the plurality of subdivisions of shapes is generated by identifying a part of the uniquely specified shape that corresponds to the sampled data, and wherein the identified parts are assembled, thereby generating a representation of the earth structures.

50. A computer readable medium according to claim 45 wherein the plurality of subdivisions are generated such that the number of parameters in each subdivision times the number of subdivisions is substantially less then would be needed using a faceted representation method, and the plurality of subdivisions is more numerically stable than third order or higher representation.

ABSTRACT

Methods and systems are disclosed for processing data used for hydrocarbon extraction from the earth. Symmetry transformation groups are identified from sampled earth structure data. A set of critical points is identified from the sampled data. Using the symmetry groups and the critical points, a plurality of subdivisions of shapes is generated, which together represent the original earth structures.

The symmetry groups correspond to a plurality of shape families, each of which includes a set of predicted critical points. The subdivisions are preferably generated such that a shape family is selected according to a best fit between the critical points from the sampled data and the predicted critical points of the selected shape family.

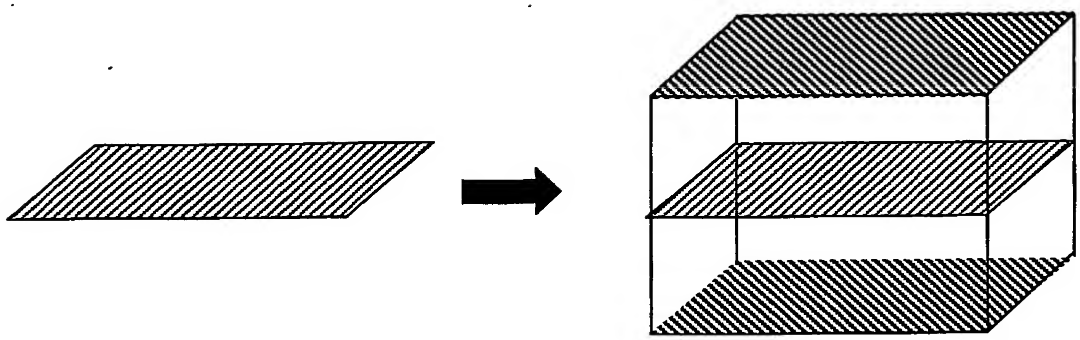


Figure 1

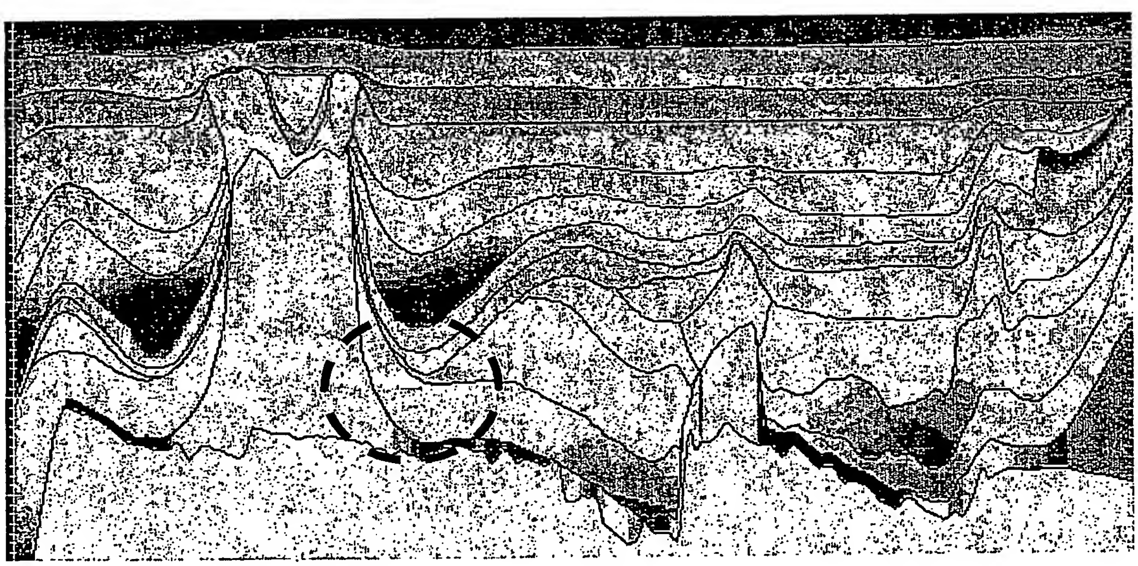


Figure 2

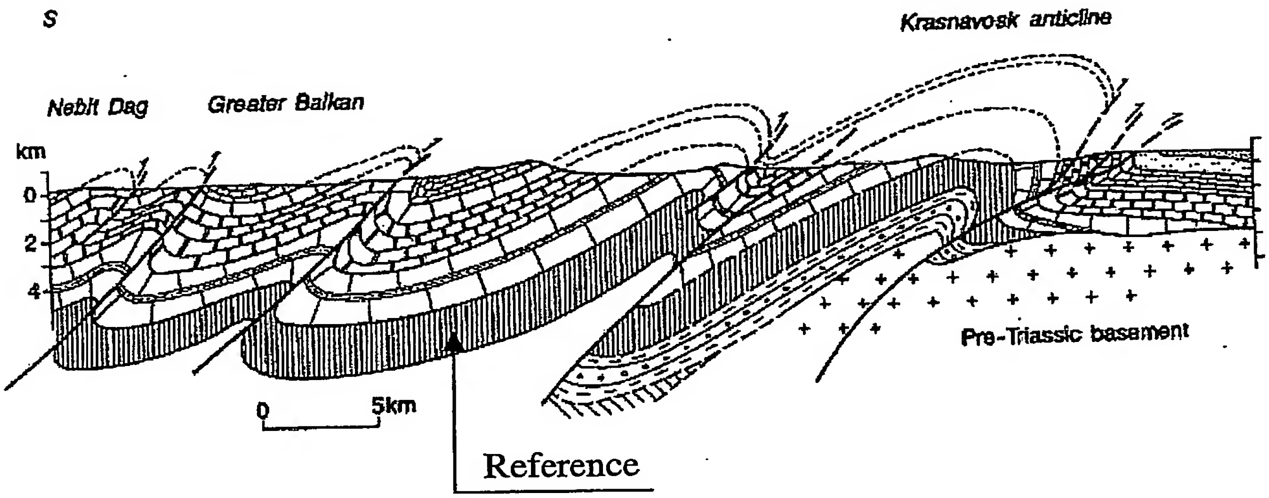


Figure 3

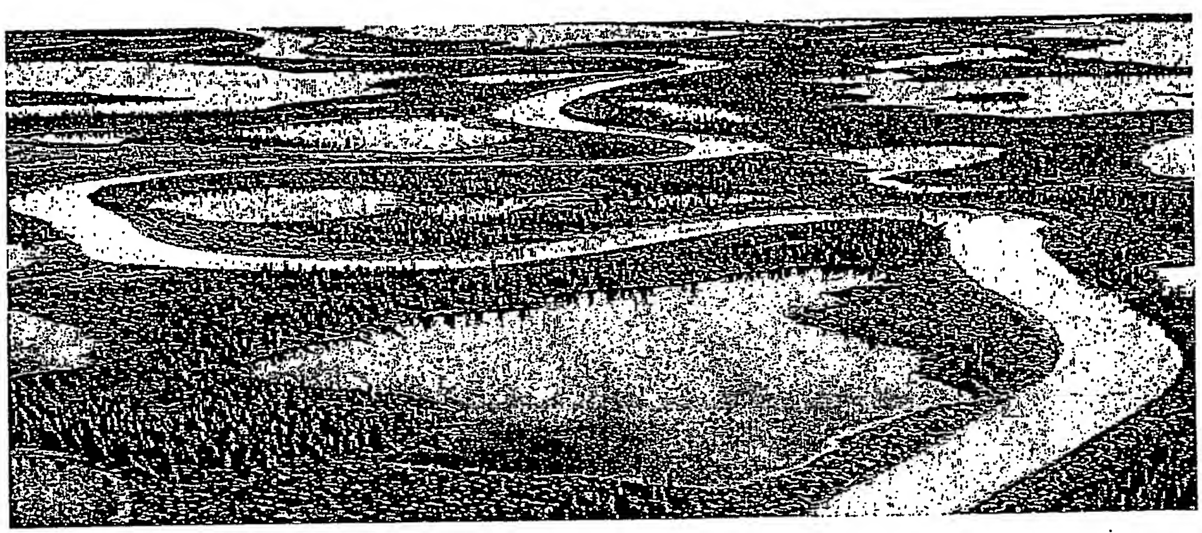
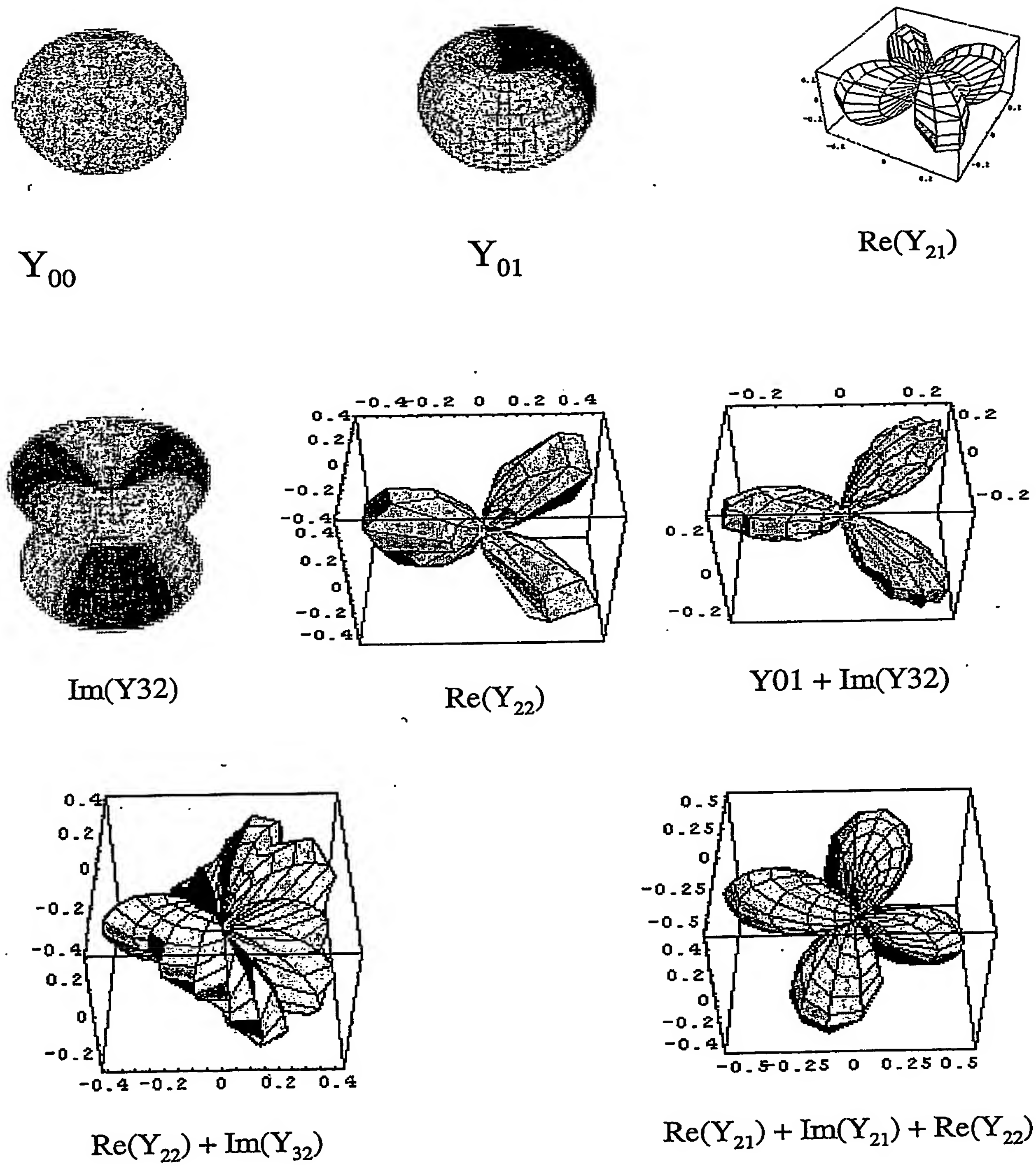


Figure 4



Y_{00} Y_{01} $Re(Y_{21})$

Im(Y32) $Re(Y_{22})$ Y01 + Im(Y32)

$Re(Y_{22}) + Im(Y_{32})$ $Re(Y_{21}) + Im(Y_{21}) + Re(Y_{22})$

Figure 5

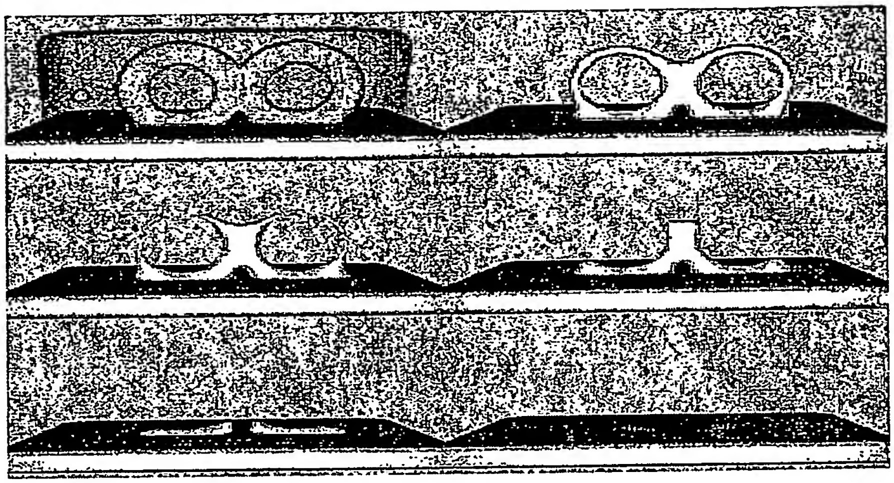


Figure 6

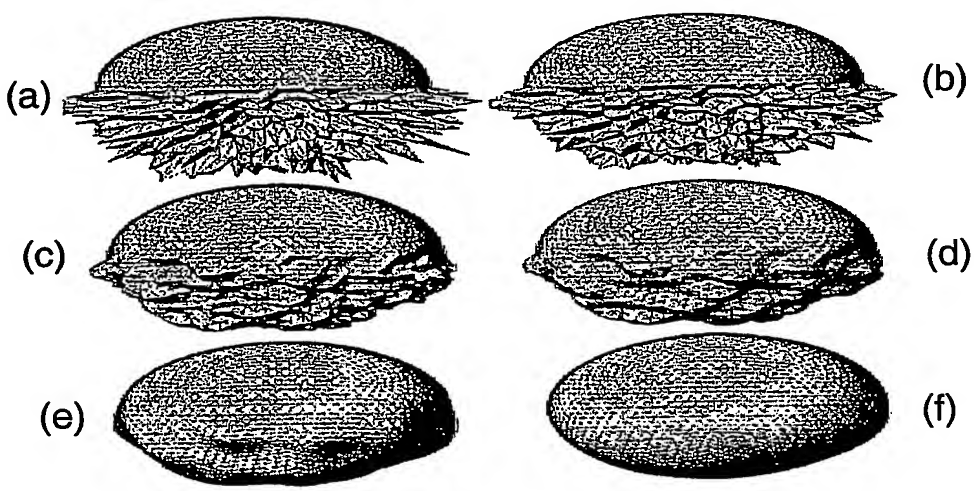


Figure 7

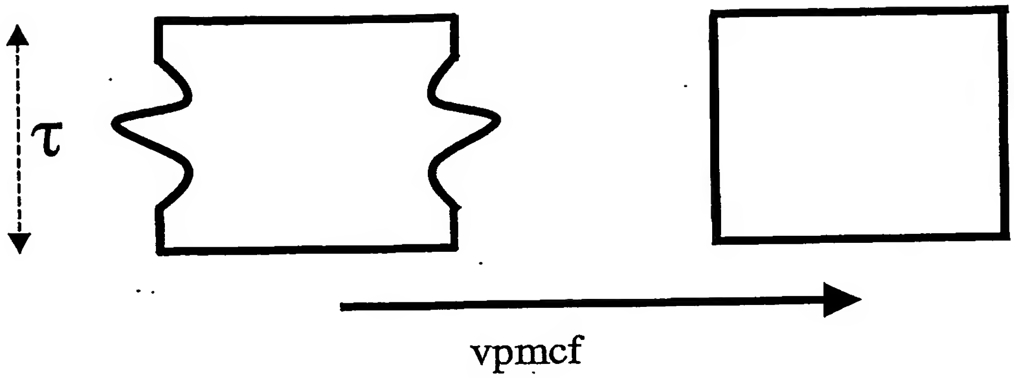


Figure 8

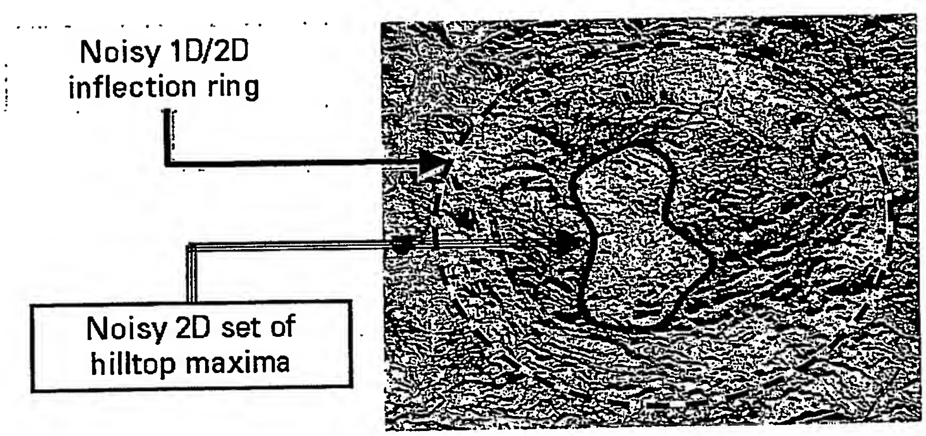


Figure 9

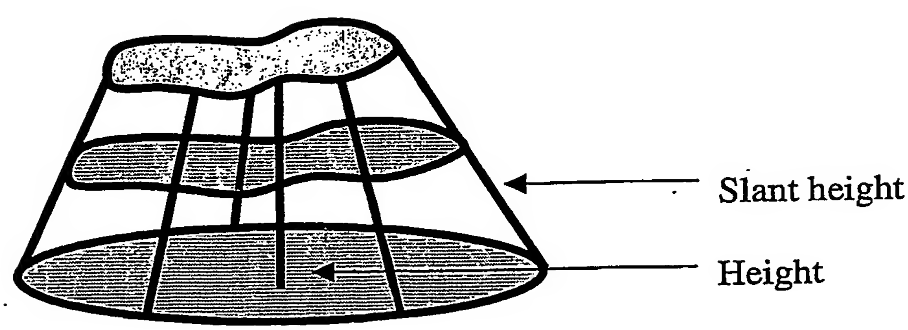


Figure 10

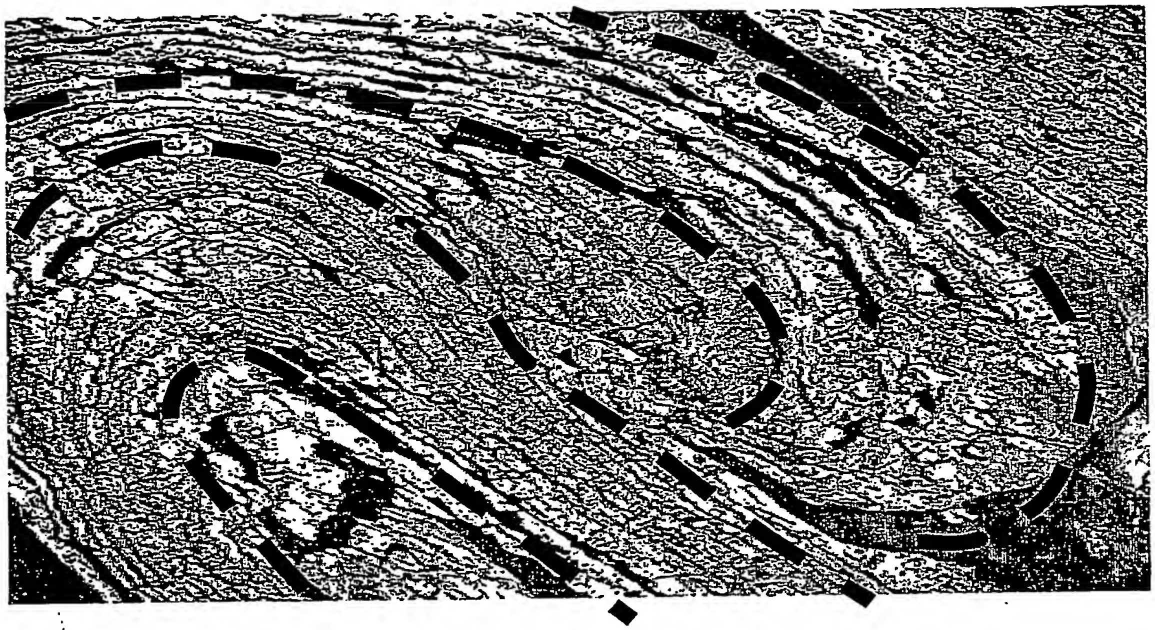


Figure 11

Figure 12

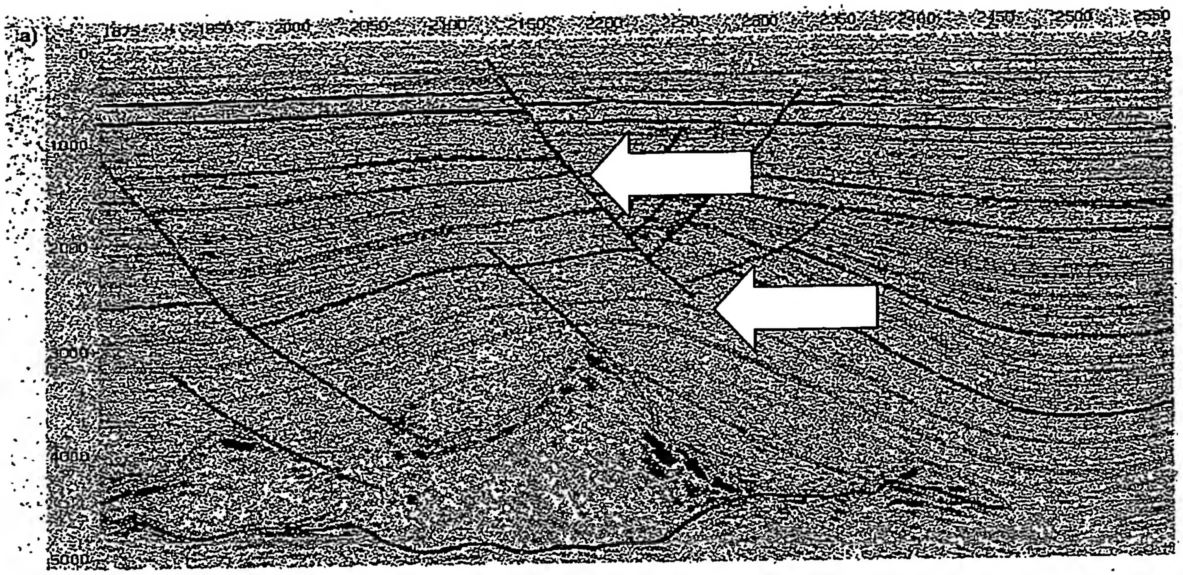


Figure 13

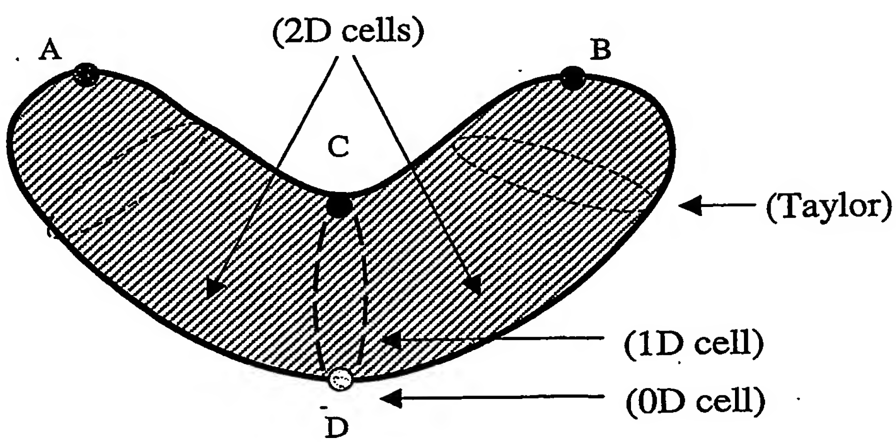


Figure 14

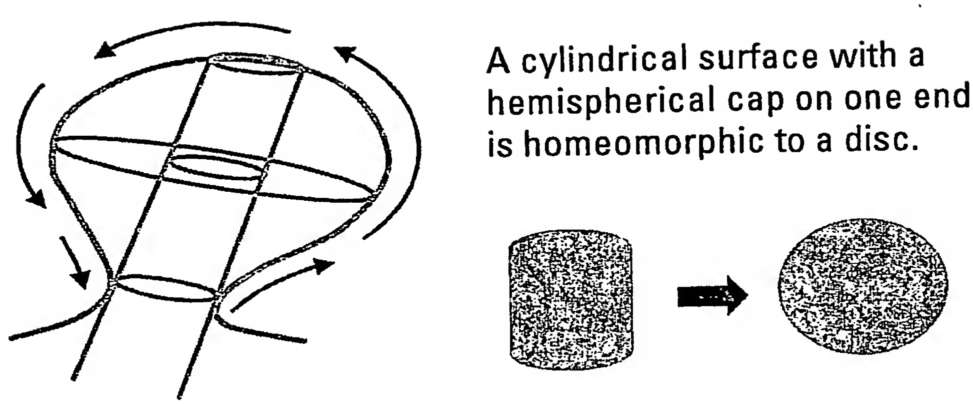


Figure 15

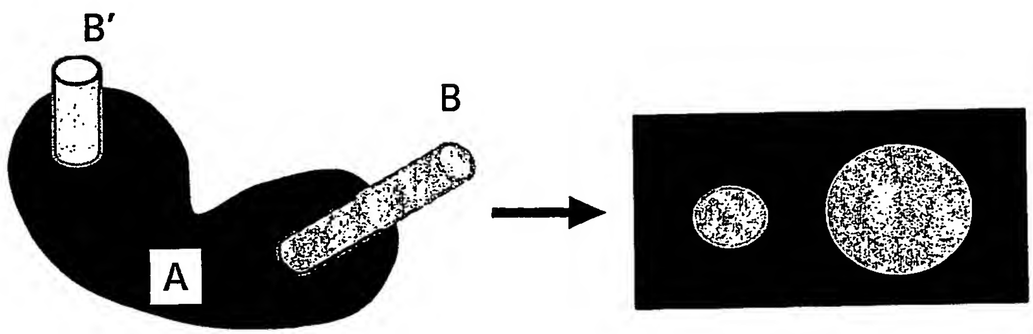


Figure 16

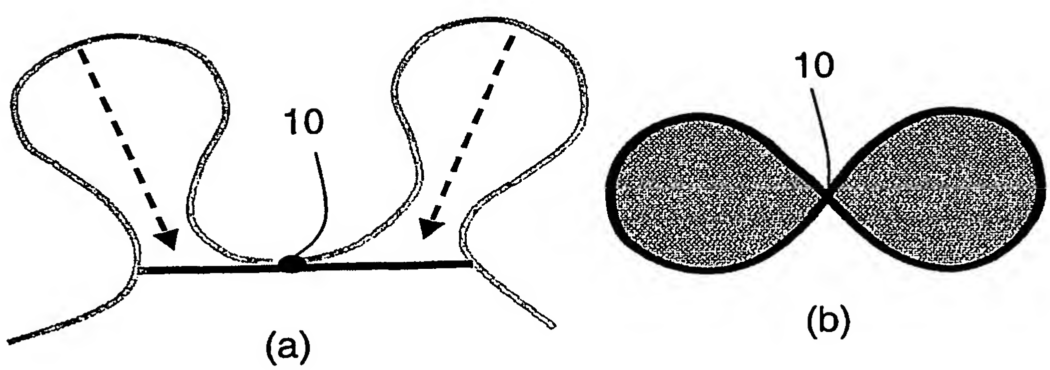


Figure 17

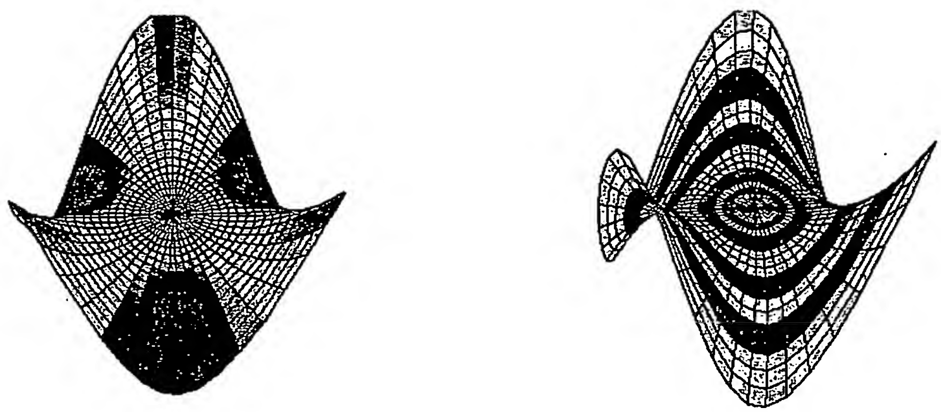
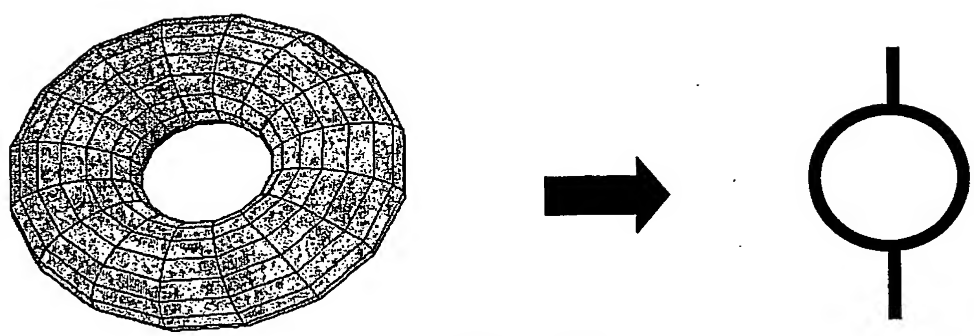


Figure 18



(a) Figure 19 (b)

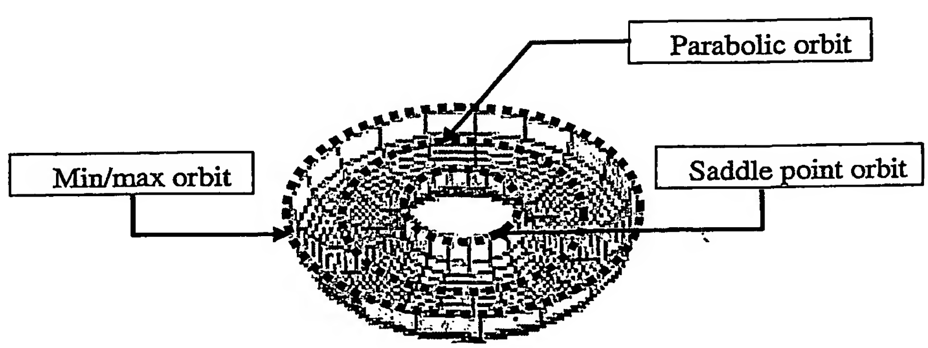
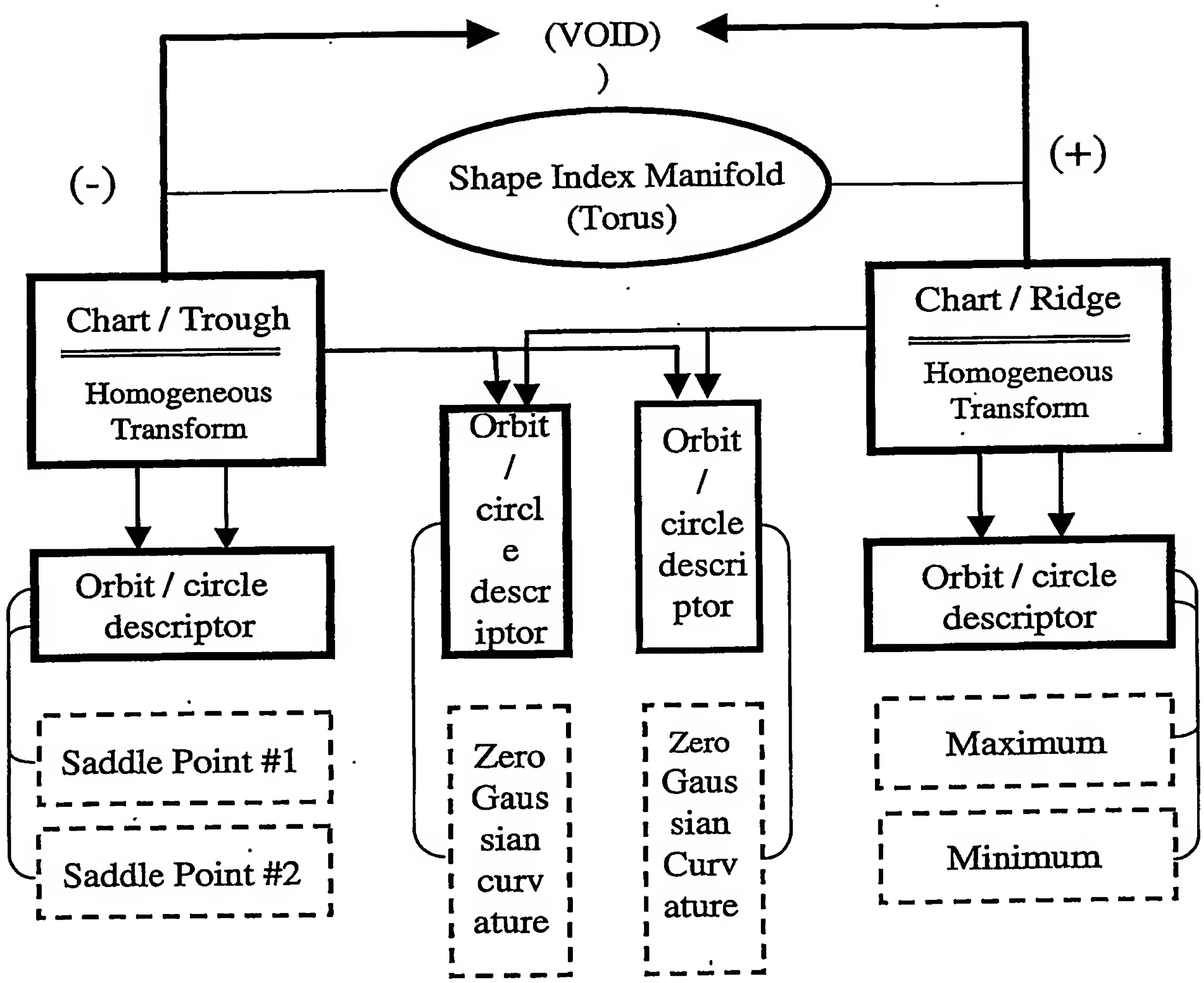


Figure 20



(VOID)
)
(-)
(+)
Shape Index Manifold (Torus)
Chart / Trough
Homogeneous Transform
Chart / Ridge
Homogeneous Transform
Orbit / circle descriptor
Orbit / circl e descr iptor
Orbit / circle descri ptor
Orbit / circle descriptor
Saddle Point #1
Saddle Point #2
Zero Gaus sian curv ature
Zero Gaus sian Curv ature
Maximum
Minimum

Figure 21

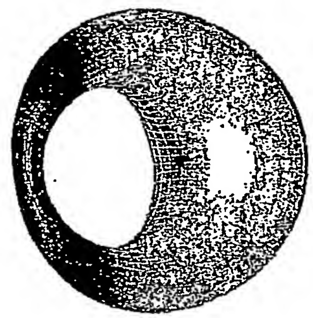
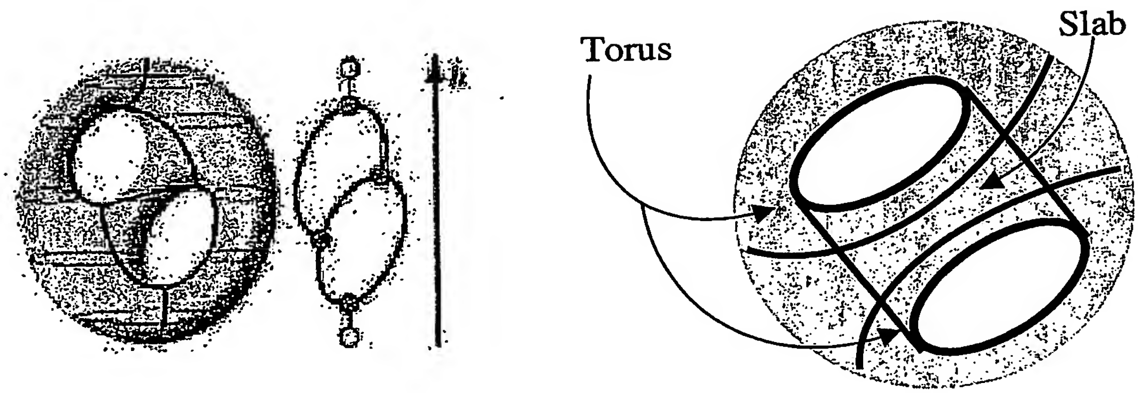


Figure 22



(a) (b)

Figure 23

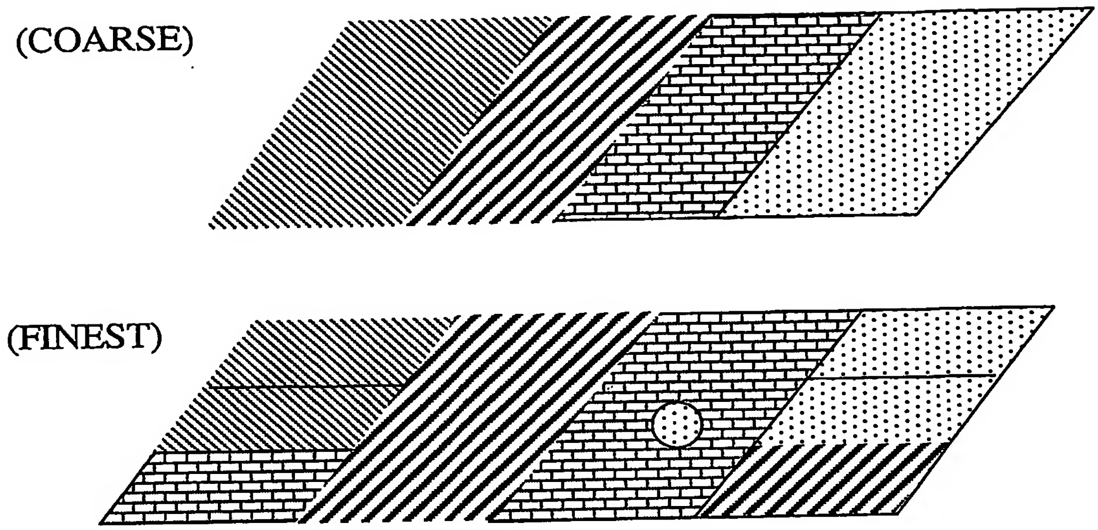


Figure 24

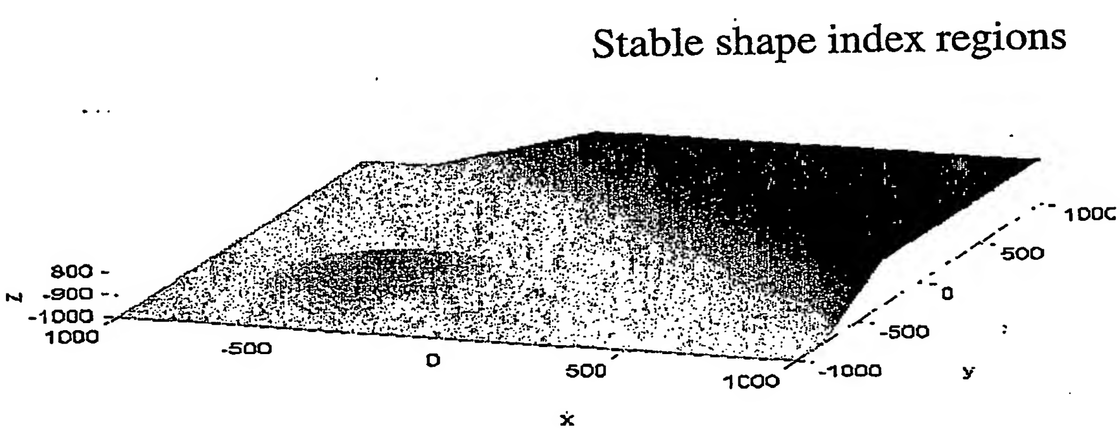


Figure 25

Figure 26

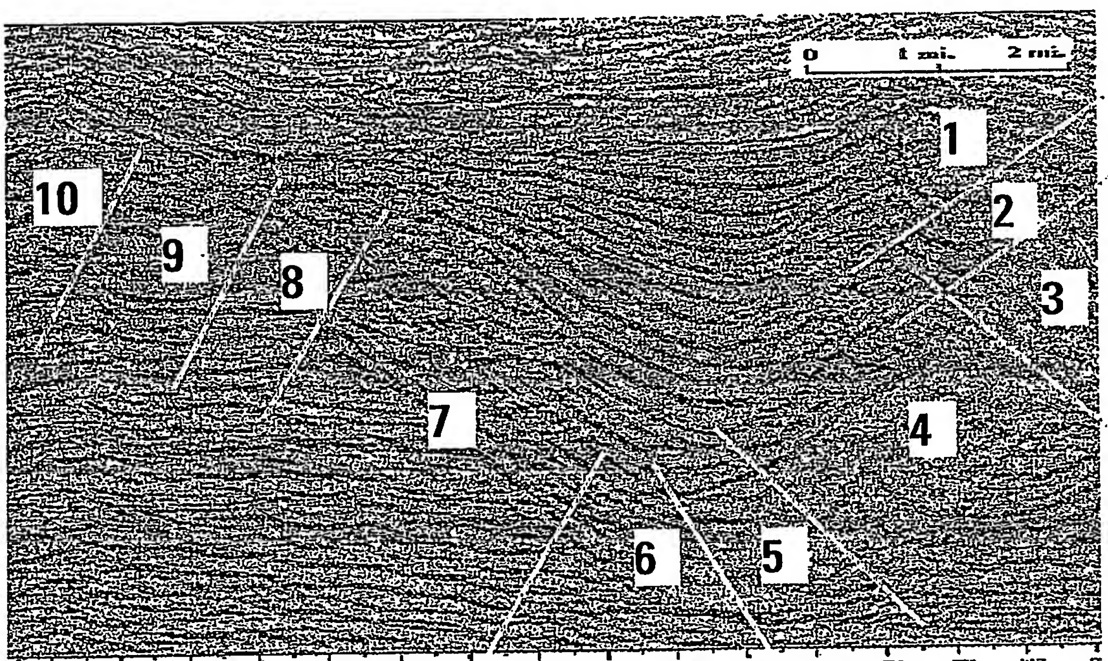


Figure 27

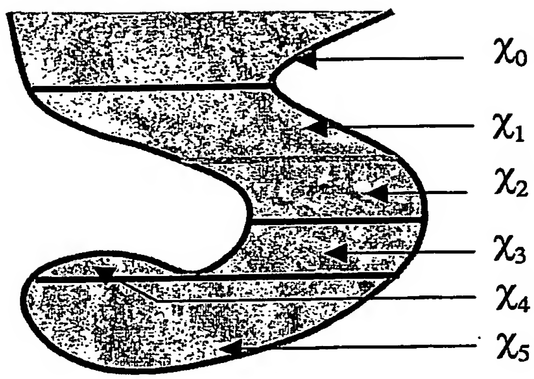


Figure 28a

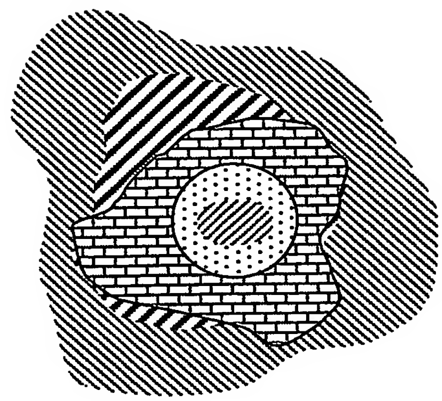


Figure 28b

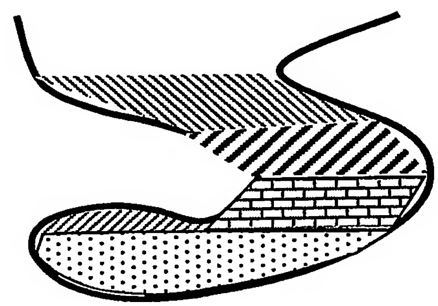


Figure 28c

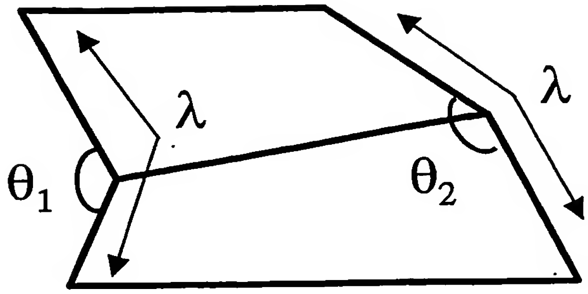


Figure 29a

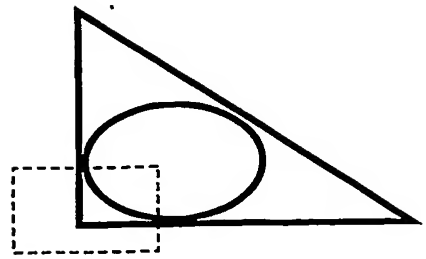


Figure 29b

$$Squeeze = \begin{pmatrix} \sin\vartheta & 0 \\ \cos\vartheta & 1 \end{pmatrix}, \ where\ 0 \le \vartheta < \pi,$$

$$Stretch = \begin{pmatrix} \sigma_x & 0 \\ 0 & \sigma_y \end{pmatrix}, \ where\ \sigma_x, \sigma_y > 0,$$

$$Blend = Stretch * Squeeze = \begin{pmatrix} \sigma_x \sin\vartheta & 0 \\ \sigma_y \cos\vartheta & \sigma_y \end{pmatrix}.$$

Figure 29c

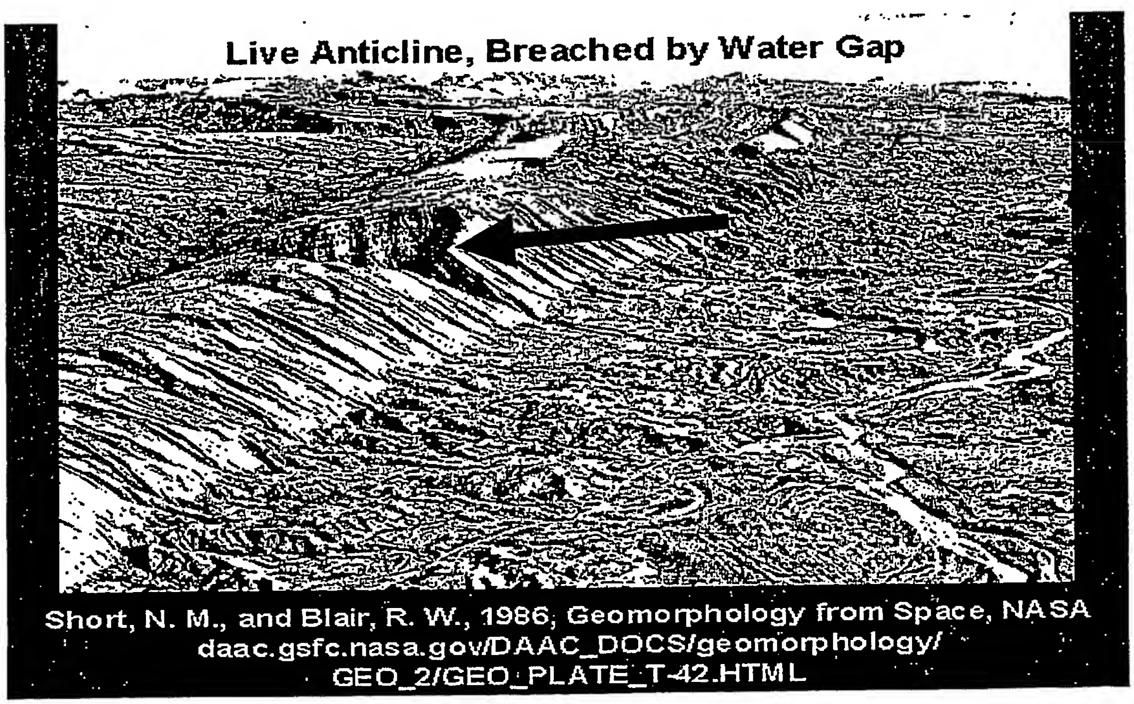


Figure 30

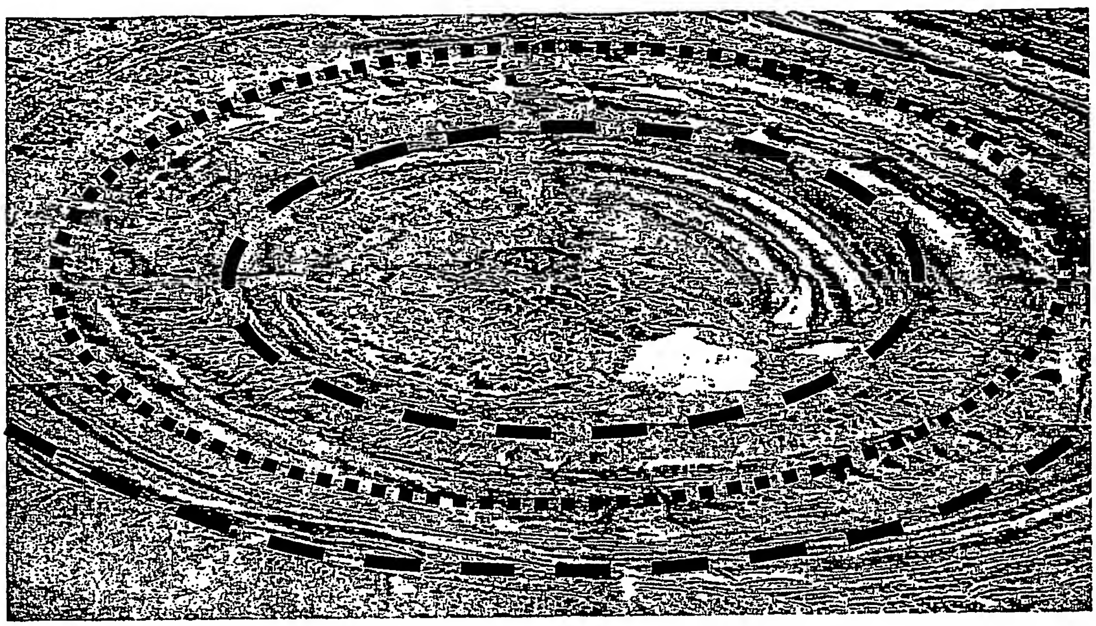


Figure 31

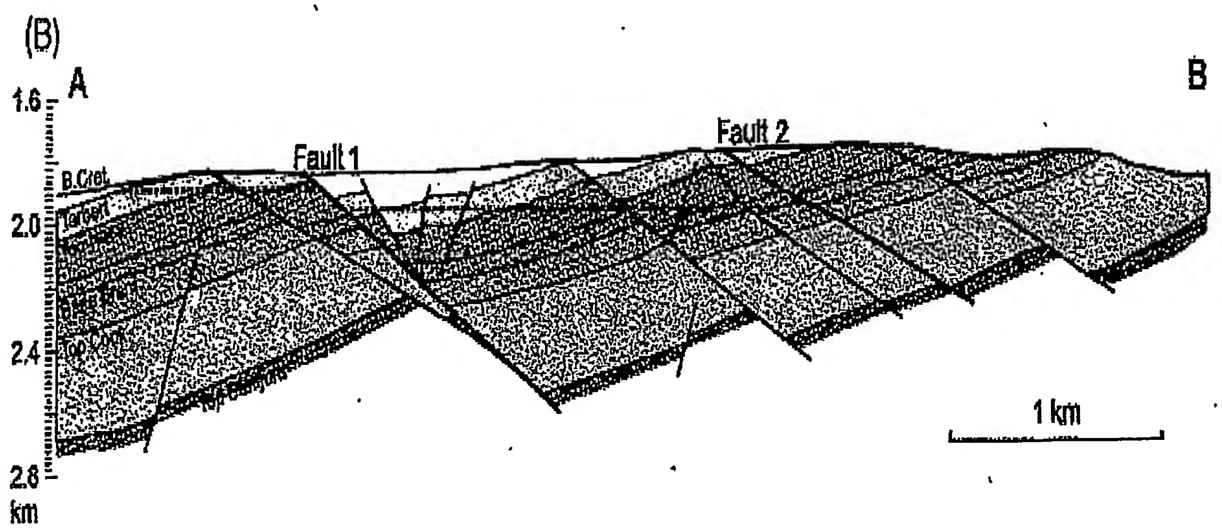


Figure 32

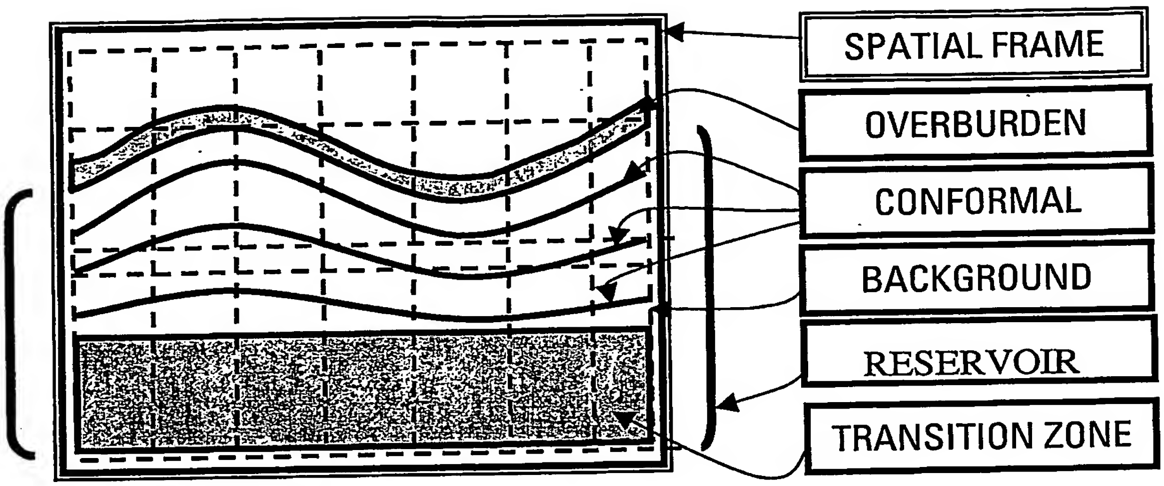


Figure 33

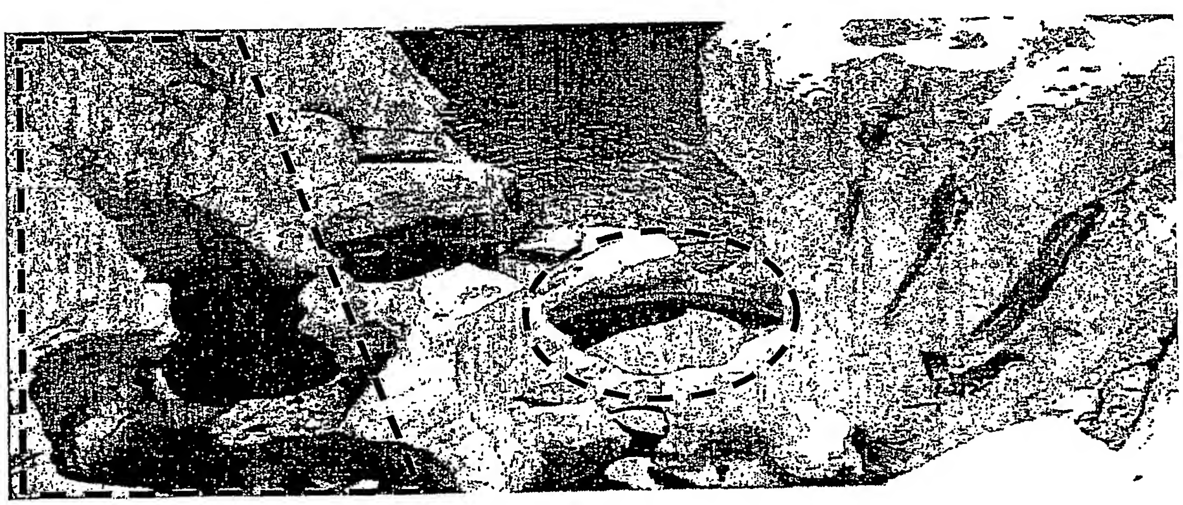
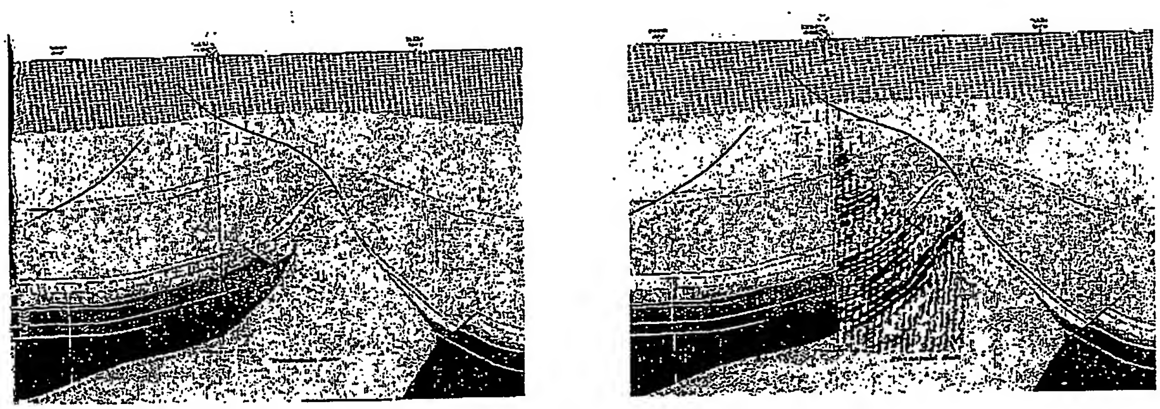


Figure 34

Figure 35



(a)

(b)

Figure 36

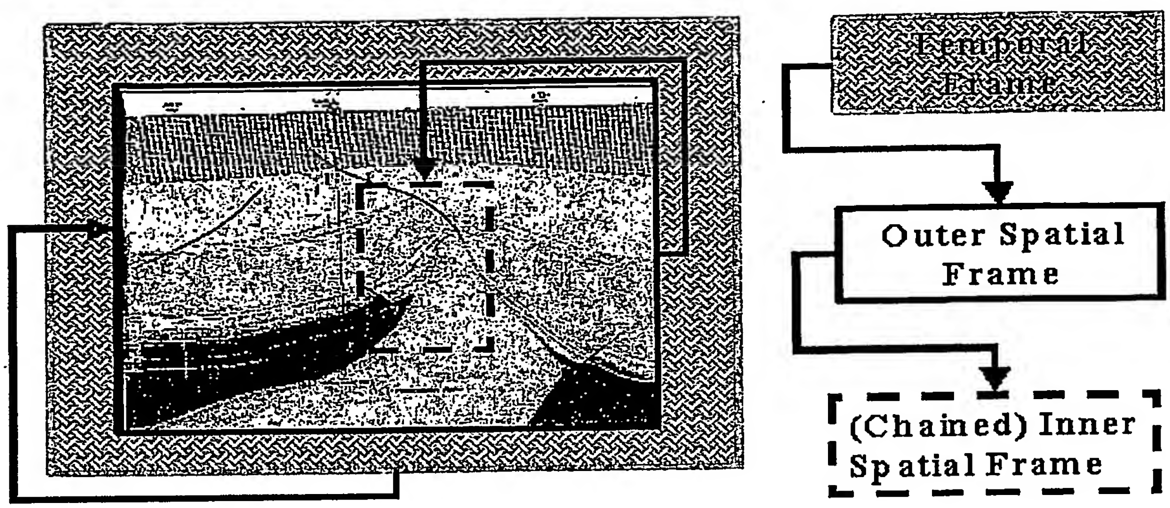


Figure 37

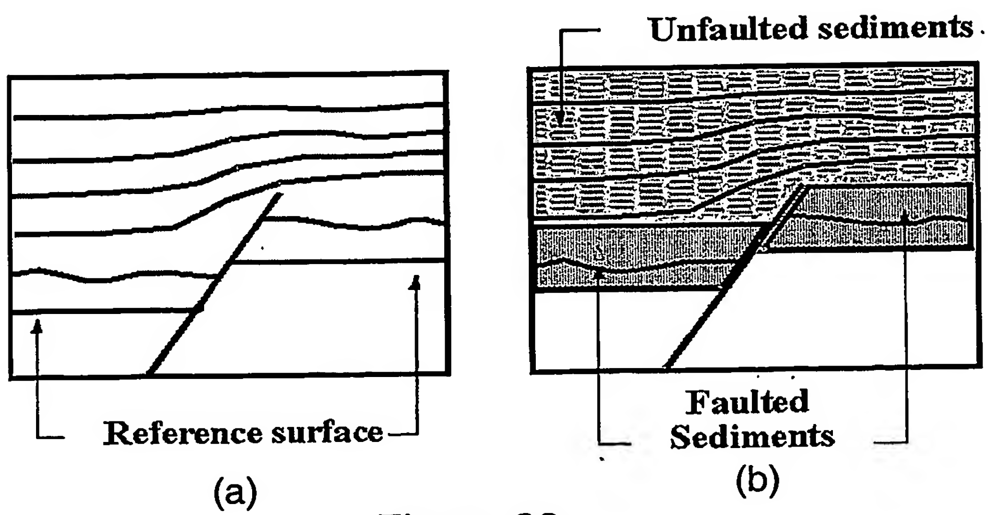
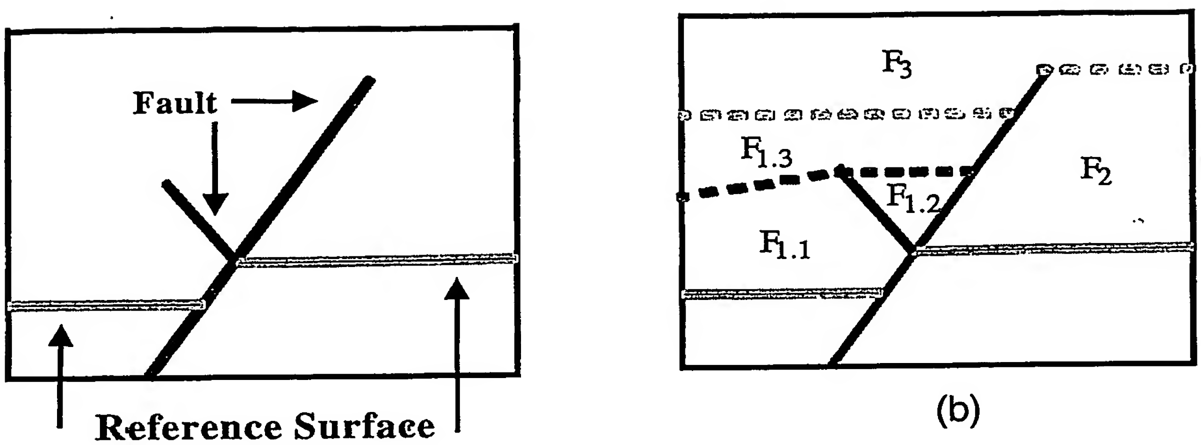


Figure 38



(a) (b)

Figure 39

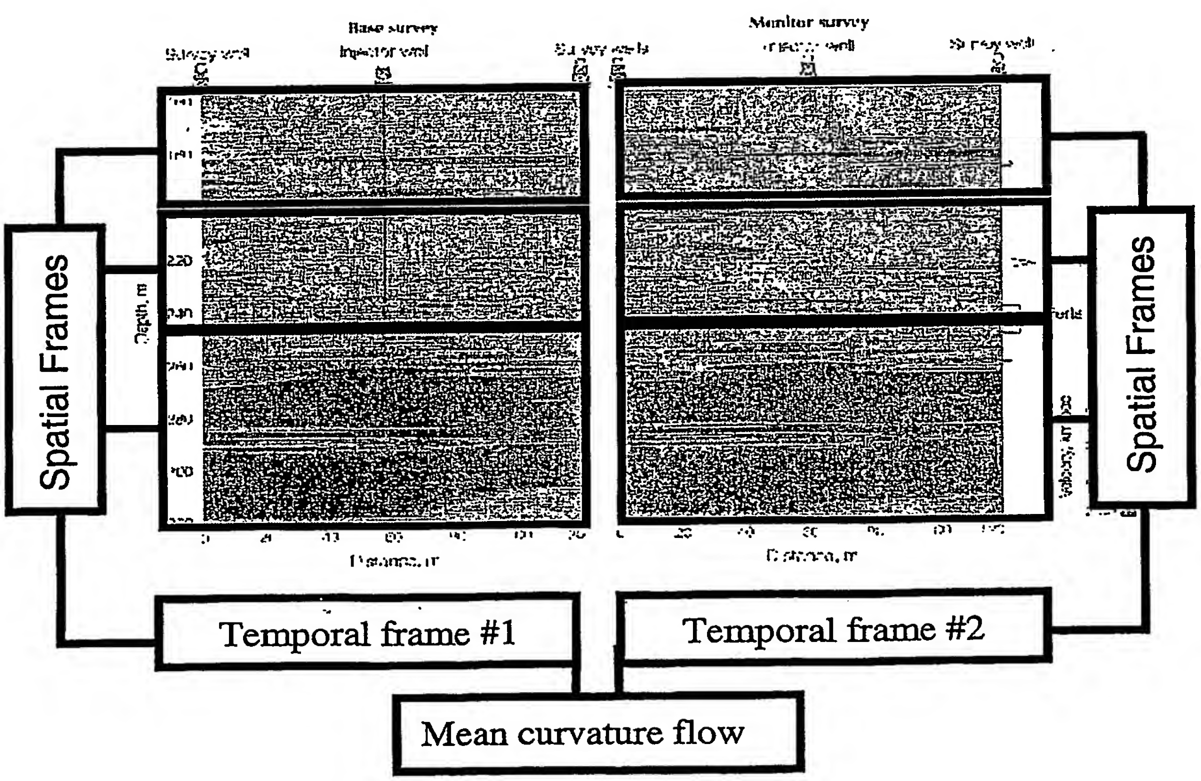


Figure 40

Spatial Frame

Name:Implicit-surface[dBase identifier]
StatusImplicit surface frame
Parent frameRegion of Interest-SF
Outer Boundary List{∂_2(S)}
Inner Frames List {E_k}
ContentsS

Spatial Frame

NameE_k
StatusElementary shape frame
Parent frameImplicit surface[dBase identifier]
Outer Boundary List{$\partial_2(E_k)$}
Inner Frames List Misfit region List
ContentsElementary shape

Spatial Frame

NameMisfit reduction region
StatusMisfit region
Parent frameE_k
Outer Boundary List{∂_2(Misfit region)}
Inner Frames List <nil>
ContentsMisfit volume

Figure 41

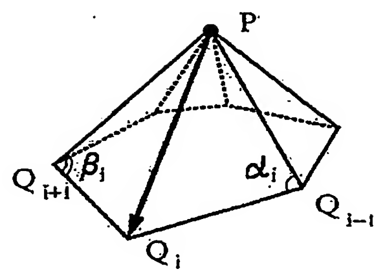


Figure 42

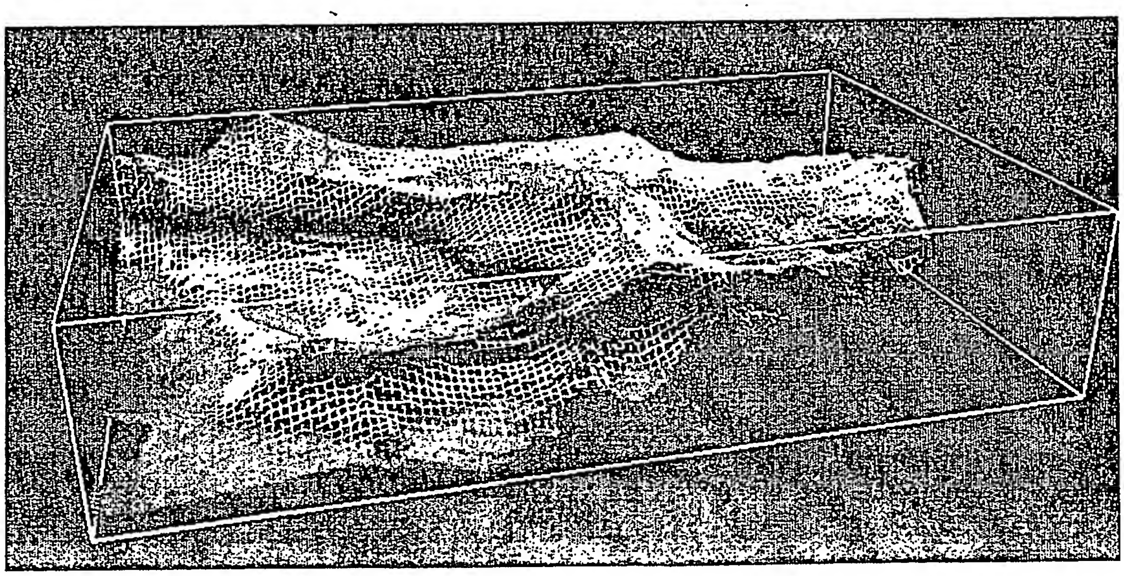


Figure 43

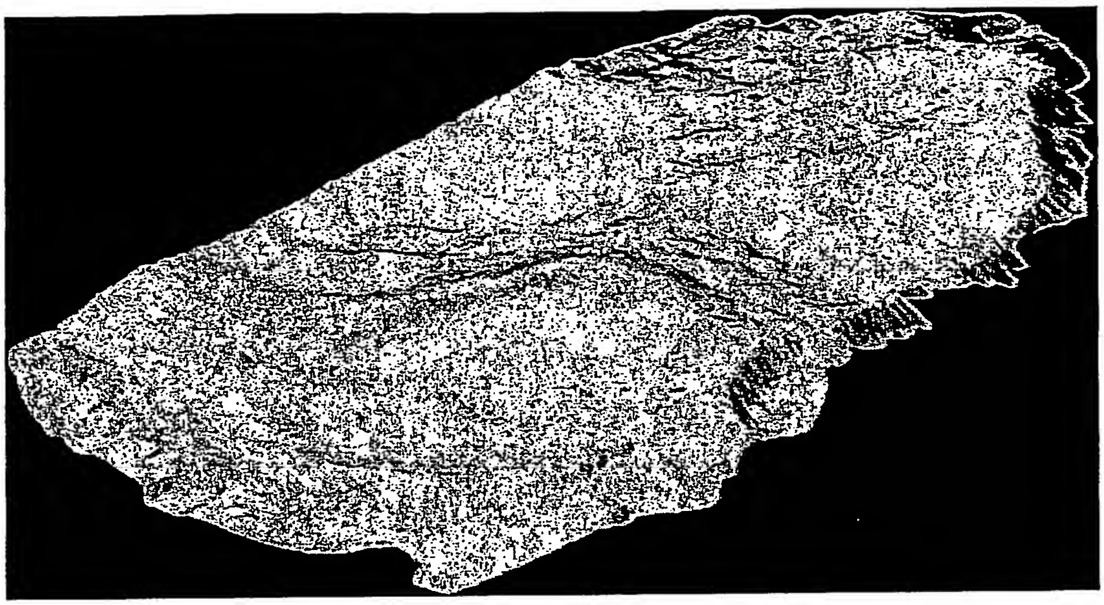


Figure 44

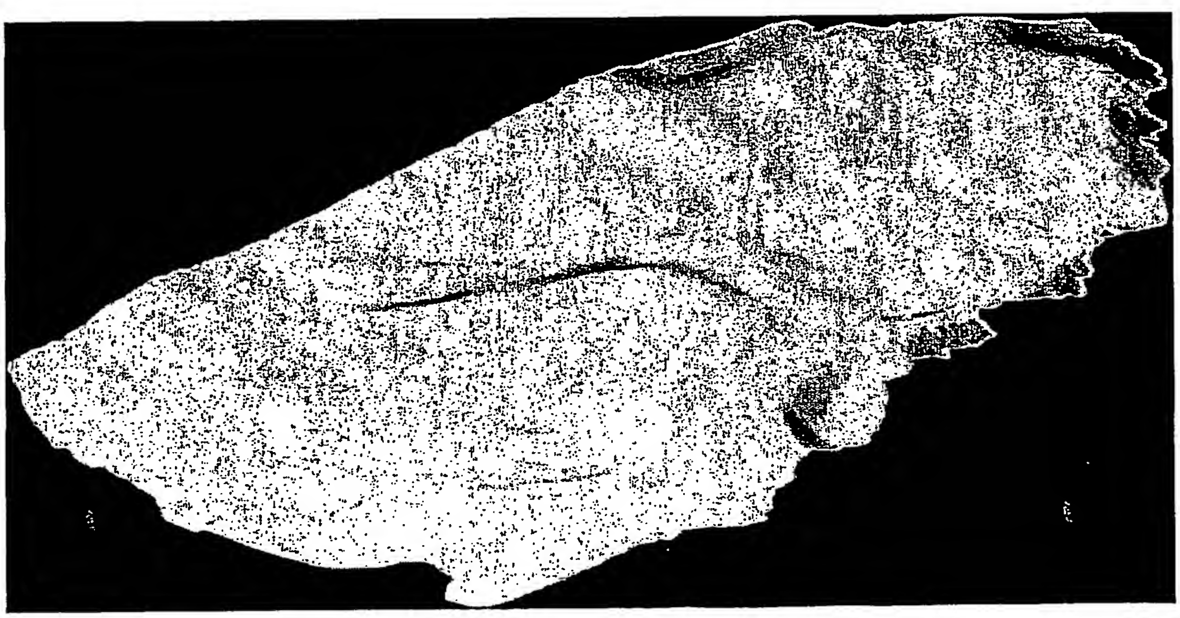


Figure 45

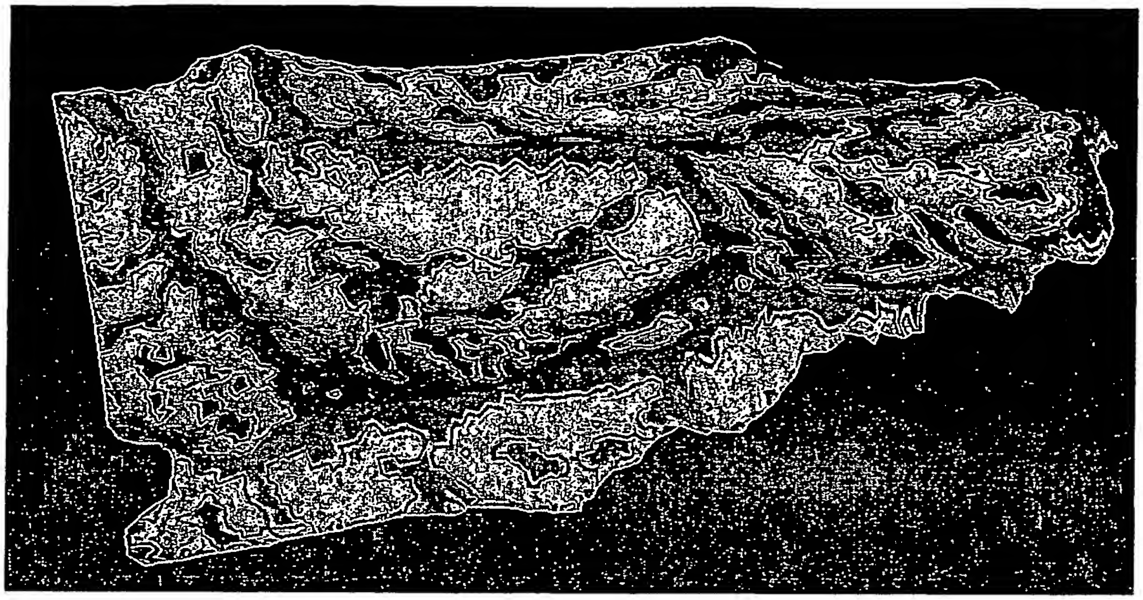


Figure 46

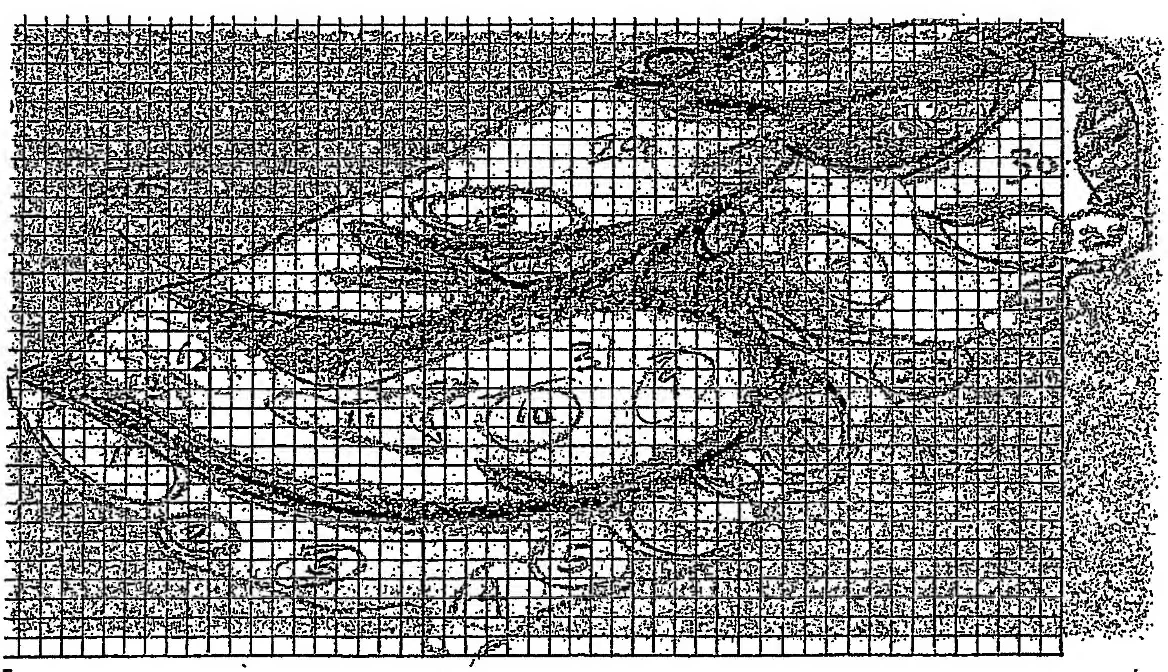
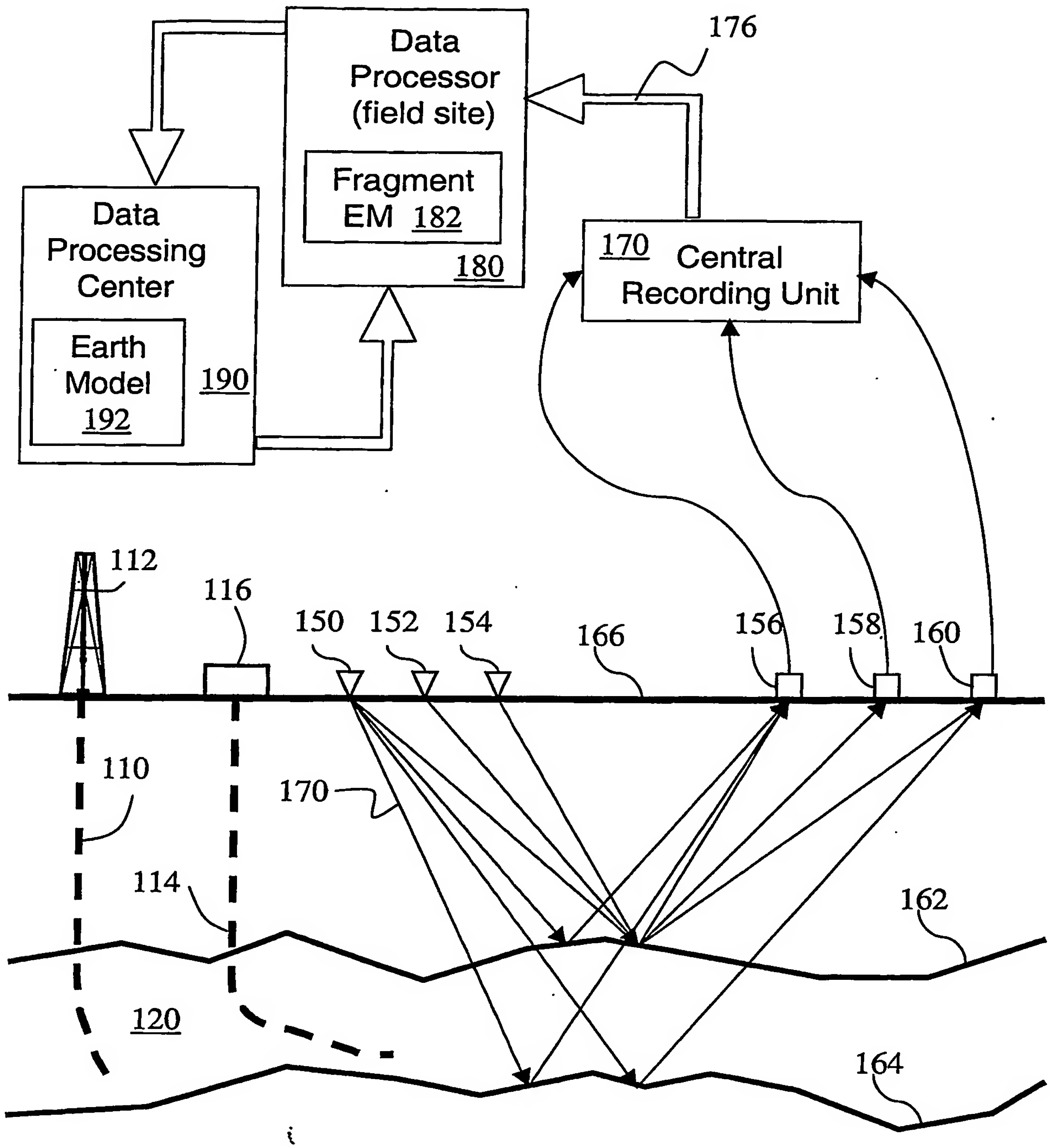


Figure 47



Data Processor (field site)
Fragment EM 182
180
176
Data Processing Center
Earth Model 192
190
170 Central Recording Unit
112
116
150
152
154
166
156
158
160
110
170
114
162
120
164

Figure 48

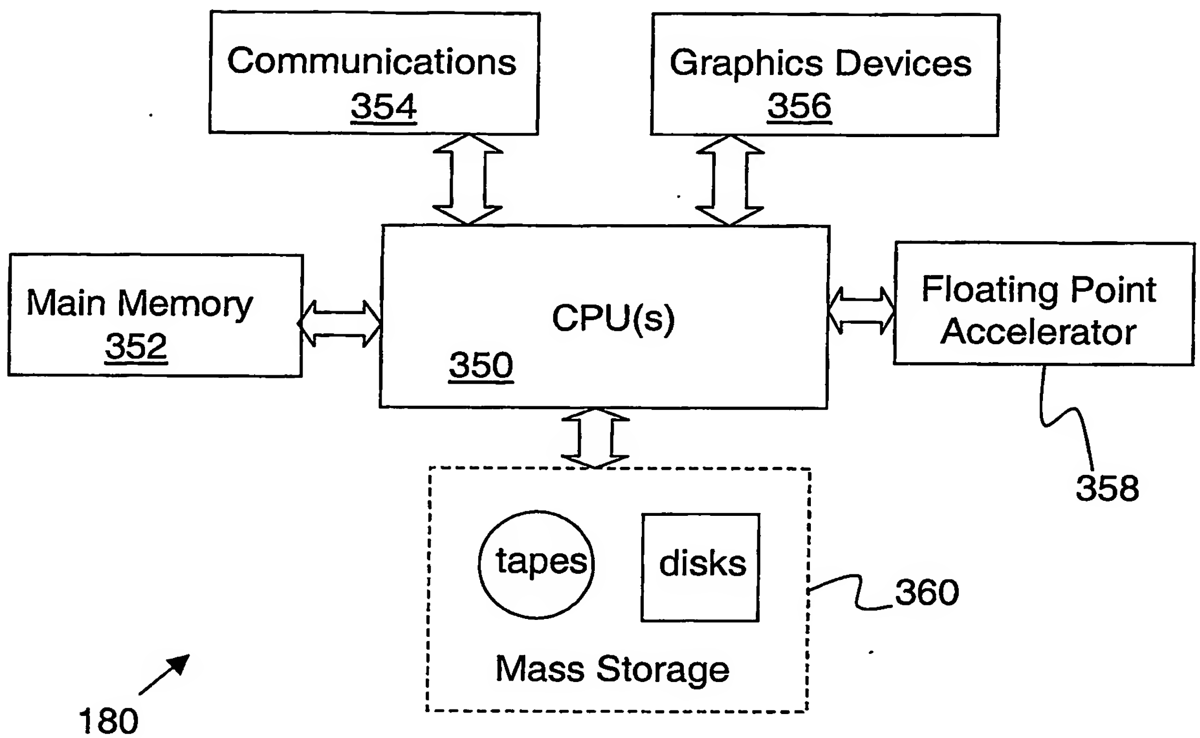

Communications
354
Graphics Devices
356
Main Memory
352
CPU(s)
350
Floating Point
Accelerator
358
tapes
disks
Mass Storage
360
180

Figure 49

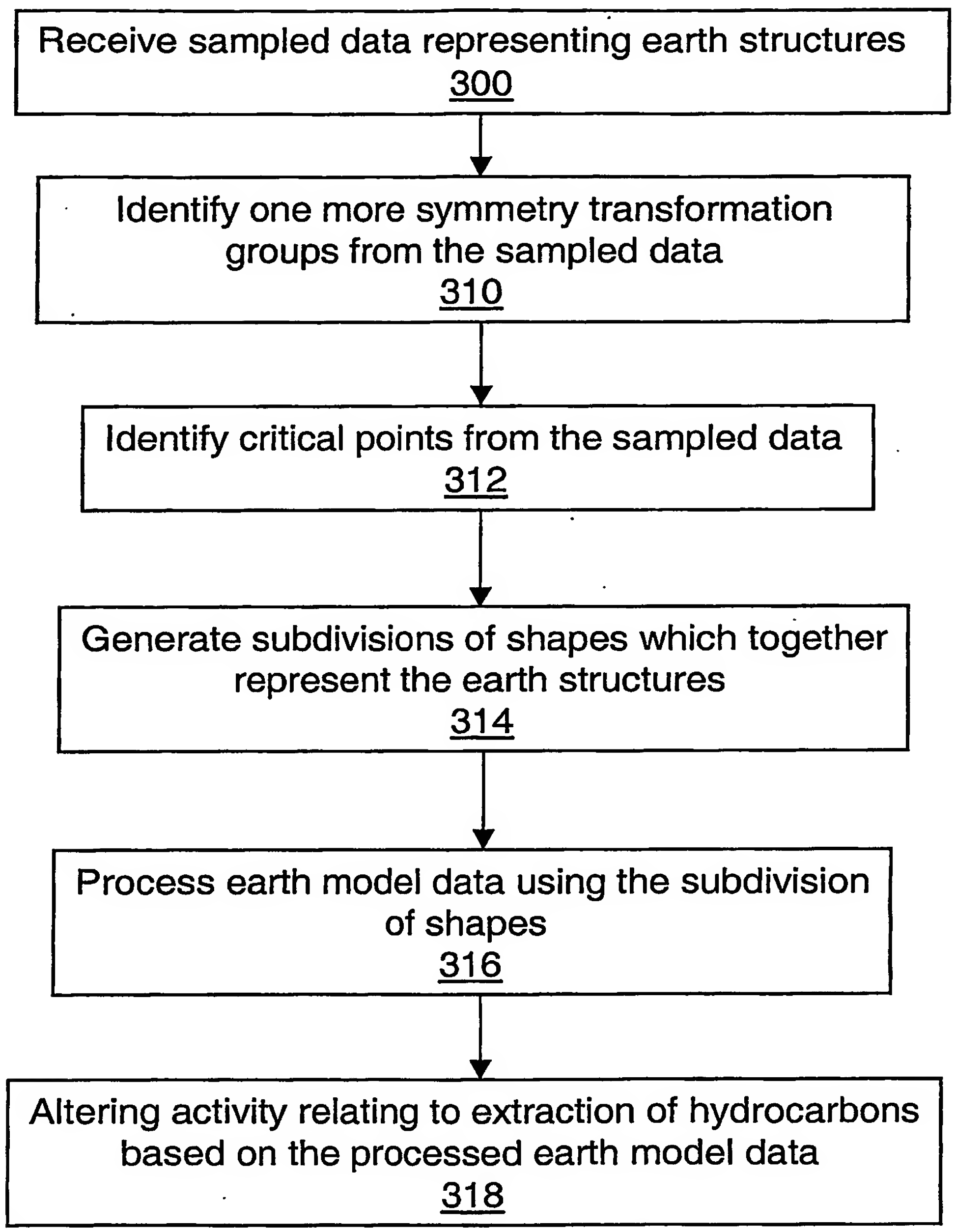

Receive sampled data representing earth structures
300
Identify one more symmetry transformation groups from the sampled data
310
Identify critical points from the sampled data
312
Generate subdivisions of shapes which together represent the earth structures
314
Process earth model data using the subdivision of shapes
316
Altering activity relating to extraction of hydrocarbons based on the processed earth model data
318

Figure 50

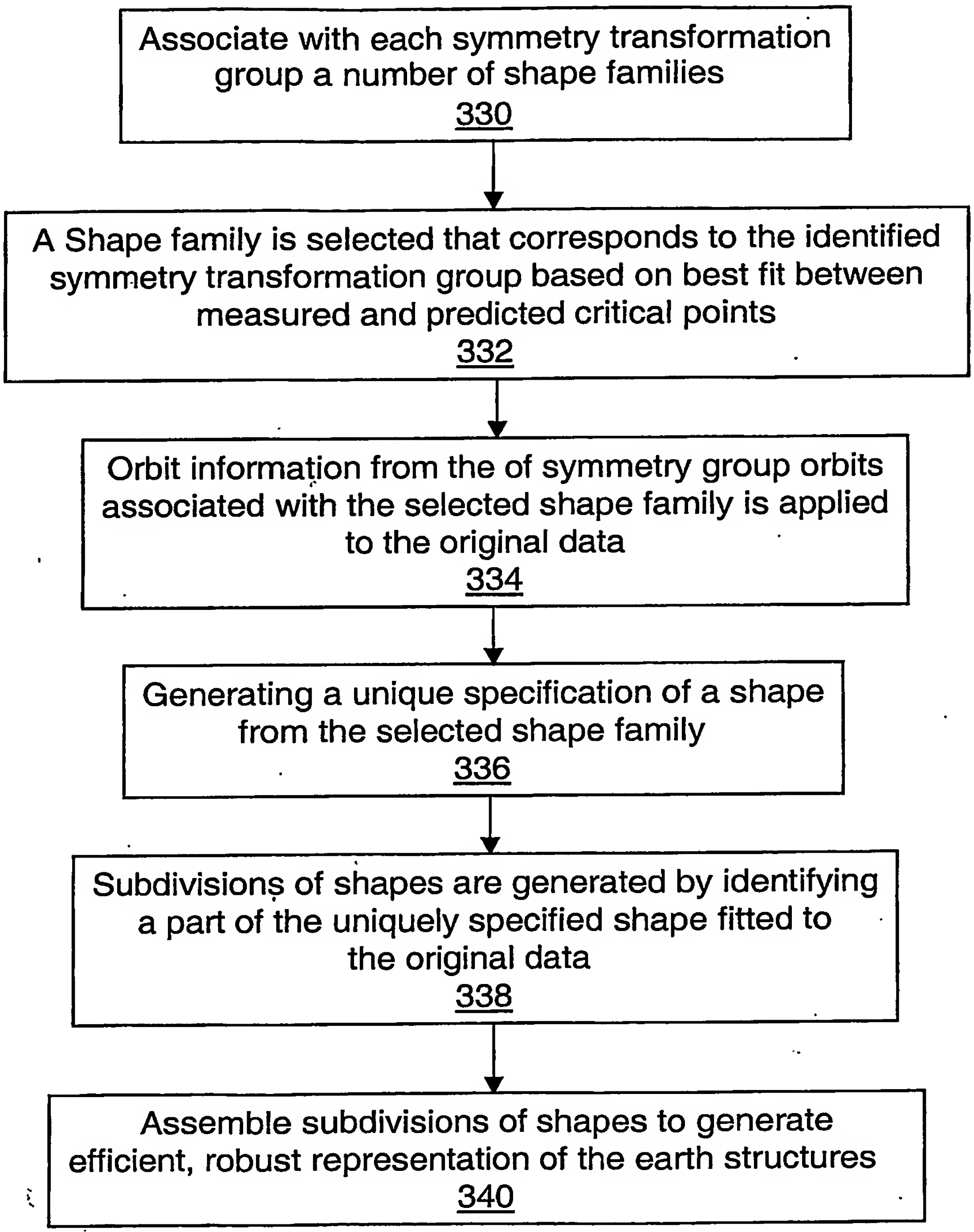

Associate with each symmetry transformation group a number of shape families
330
A Shape family is selected that corresponds to the identified symmetry transformation group based on best fit between measured and predicted critical points
332
Orbit information from the of symmetry group orbits associated with the selected shape family is applied to the original data
334
Generating a unique specification of a shape from the selected shape family
336
Subdivisions of shapes are generated by identifying a part of the uniquely specified shape fitted to the original data
338
Assemble subdivisions of shapes to generate efficient, robust representation of the earth structures
340

Figure 51